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Fire barrier penetrations – Interactions between concrete and sealing materials

Master´s thesis which has been submitted for Master of Science degree.
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Abstract of master's thesis

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Abstract

Fire compartmentation is a crucial part of fire safety of buildings. Effective fire barriers are needed for effective fire compartmentation. Fire barrier is easy to design and manufacture if there is no penetrations in the structure. Penetrations cause problems in terms of integrity of fire barrier. In this case firestops determine the effectiveness of fire barrier against fire.

This thesis discusses different rules and regulations controlling the design and manufacture of firestops. Firestop regulations are going through transition phase, and there are many regulations and rules to follow. CE-marking of construction products is the biggest individual change affecting firestops and it is discussed in more detail.

Two case studies of different kinds of building fires were conducted to evaluate the importance of firestops. These case studies together with literature review acted as a basis for the experimental study.

In experimental study 5 different sealing materials were used to construct small scale penetrations in concrete pieces with plastic pipes. These samples were exposed to high temperatures for different times. After exposure samples were studied for changes in sealing materials as well as concrete. Visual inspection and SEM were used to study the changes.

Keywords fire, fire barrier, firestop, sealant,

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Tiivistelmä

Palo-osastointi on tärkeä osa rakennuksen paloturvallisuutta. Tehokkaan palo-osastoinnin edellytyksenä ovat toimivat paloseinät. Paloseinien ja -muurien suunnittelu ja toteutus on helppoa, jos rakenteessa ei tarvita läpivientejä. Läpivienneistä aiheutuu ongelmia rakenteen yhtenäisyyden ja tiiveyden kannalta. Tässä tapauksessa palokatkot määrittävät paloseinän toimivuuden tulipalotilanteessa.

Tässä diplomityössä käydään läpi asetuksia ja ohjeita, joilla säädellään palokatkojen suunnittelua ja toteutusta. Säännökset ovat muutosvaiheessa ja noudatettavana on useita sääntöjä. Rakennustuotteiden CE-merkitsemiskäytäntö on suurin yksittäinen palokatkoihin vaikuttava muutos ja sitä käsitellään tarkemmin.

Kahdesta erilaisesta tulipalosta tehtiin case-tutkimukset, joiden tarkoituksena oli valottaa palokatkojen merkitystä. Nämä tutkimukset yhdessä kirjallisuustutkimuksen kanssa toimivat lähtökohtana kokeelliselle tutkimukselle.

Kokeellisessa tutkimuksessa viidestä erilaisesta palokatkomateriaalia käytettiin betonin ja muoviputken kanssa pienen mittakaavan läpiviennin tekemiseen. Nämä näytteet altistettiin vaihtelevin ajoin korkeille lämpötiloille. Lämmityksen jälkeen näytteistä tutkittiin muutokset palokatkomateriaaleissa ja betonissa. Tutkimus toteutettiin visuaalisesti sekä hyödyntäen SEM-tutkimusta.

Avainsanat tuli, tulipalo, palokatko, paloseinä, palomuuri, saumamassa

Foreword

First I must thank all the people at tremco Illbruck for support and guidance during my work and especially I would like to thank Country manager Ville Teerioja for suggesting me to study firestop materials. Great thanks goes also to Timo Saari and Petri Koivuniemi for providing me additional information and tips on the subject.

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Special thanks must be handed to my family for support during my studies and finally the greatest thanks goes to my beloved partner Jeanna, for supporting and having the strength to cope with my mood swings, frustration and long working hours. Finishing of my thesis would not have been possible without anyone of the people mentioned.

Lohja 26.4.2014

Sami Järvinen

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Definitions

DoP: Declaration of Performace is drawn up by manufacturer when a product covered by hEN or ETA is placed on the market. It delivers the information about the essential characteristics of his product. Manufacturer assumes the responsibility for the conformity of the construction product with the declared performance. CE-marking follows the DoP. (European Comission, 2013.)

CE-mark: CE-mark is a label affixed to a construction product for which manufacturer has drawn up a Declaration of Performance. It is a sign that specific product fulfils the requirements set by regulation EU/305/2011. It also means that the manufacturer has followed all the applicable procedures for drawing up his DoP, and the DoP is accurate and reliable (European Comission, 2013).

CPD: The European construction product directive, 89/106/EEC, aims to remove barriers of trade for construction products between members of EU (Sundström, 2007). CPD is replaced by CPR.

CPR: The European construction products regulation. Regulation (EU) No 305/2011 of the European Parliament and the council.

EAD: European Assessment Document is the basis for the issuing of ETAs according to the new EU/305/2011.

ETA: *Before 1st of July 2013:* European Technical Approval is based on ETAG or issued upon common agreement of the Approval Bodies. These type of ETAs will disappear throughout the year 2018 according to EOTA (European Organisation of Technical Assessment, 2013).

ETA: A*fter 1st of July 2013:* European Technical Assessment is a document based on EAD which provides information on the assessment of the performance of a construction product, in a relation to its essential characteristics. (Construction Products Regulation EU/305/2011).

ETAG or **ETA guidelines:** European Technical Assessment Guidelines were the basis for issuing of ETAs before the Construction Products Regulation EU/305/2011 took place in 1st of July 2013.

feed-through or service penetration: These both refer to a hole which is needed in fire barrier structure usually to pass through electrical wirings, pipings or other technical equipment.

firestop: Firestop is commonly known as the sealing of penetration in a fire compartment wall. Main purpose of firestop is to retain the walls properties at the same level than before the penetration.

fire compartment: Fire compartment is a defined part of building structure, a room, hallway or a larger area, from where the spreading of fire is prevented during a given time span.

fire sealing: Sealing of structure joints and penetrations in a fire compartment wall, floor or ceiling with proper fireproof sealants.

HPC: High-Performance Concrete.

OPC: Ordinary Portland Concrete.

PFP: Passive Fire Protection. This means all the components whose purpose is to prevent and limit the spreading of fire and combustion gases.

PP: Polypropylene.

SEM: Scanning Electron Microscopy.

third party statement: Statement that proves products usability in a specific case which is tested. In Finland this is issued usually by VTT.

TAB: Technical Assessment Body is in charge of the technical assessment of construction products and issues the European Technical Assessment. For example in Finland the only TAB is VTT Expert Services Oy. (European Organisation for Technical Assessment, 2013.)

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1 Introduction

1.1 Background

Building fires kill thousands of people every year all over the world. In Finland building fires are often result of a human error or carelessness with fire. Nevertheless as seen on news lately fires can be caused by faulty electrical wiring or equipment malfunction. Despite previously mentioned facts, nearly one third of every building fire is being lit up by an arsonist. This leads to a conclusion that building fires can never be fully prevented. Even with the most cautious design and construction work there's always a little chance that building is going to catch fire in some part of its life cycle either by intentionally or accidentally.

Fire safety involves many different aspects. It is a combination of designing structures of a building correctly, designing efficient fire compartmentation and constructing the building in the way it was designed. This is also true for renovating buildings. Awareness of these aspects is greatly grown, but there are still many facts that remain unclear or are misunderstood. Also, when trying to cut expenses it is easy to overlook things that are not visible after completion of construction. Unfortunately, firestops are one of these parts of construction.

This thesis discusses only firestops used in technical feed-throughs as a part of fire separating structures. This includes feed-throughs done because of HPAC (heating, plumbing, air-conditioning) and electrical installations. In more detail focus is on recommendations and solutions of fire stops and materials used in them. This thesis also takes a look at CE-mark regulations and the present state of firestop products in Finland. This thesis doesn't take into account fire-doors, windows or hatches or any other products that are used in opening protection.

1.2 Research material and methods

1.2.1 Research material

Research material consists of different kinds of documents relating to fire safety and firestops. These include laws, regulations and recommendations from different authorities. Case studies are based on documentation made by Onnettomuustutkintakeskus. Manufacturing of test samples, used in experimental study, was done according to suggested measurements of joint dimensions set by technical data sheets of used firestop mastics.

1.2.2 Research methods

This study documented cases of building fires. Cases differ from each other by the scale of destruction, reasons for spreading of the fire and largely for the design of fire compartmentation and passive fire protection.

Experimental part of thesis studies the behaviour of commonly used firestop materials in combination with concrete. The purpose was to compare the differences, between normal strength concrete and high strength concrete in behaviour with firestop mastics. The behaviour was studied at first in normal condition (temperature of 20˚C) and then at high temperatures. The experimental part acts as a scope to the future, because demand for better fire resistant building materials is increasing.

1.2.3 Aim of research

Research has few aims that can be recognized as follows. First aim is to clarify the process of CE-marking firestop products and the situation of other methods to approve products suitability in construction. Second aim was to identify some common failures in designing and making of firestops in construction, by studying two cases of actual building fires. Third aim was to experiment and study commonly used firestop materials in combination with concrete exposed to high temperatures.

2 Review of literature and regulations

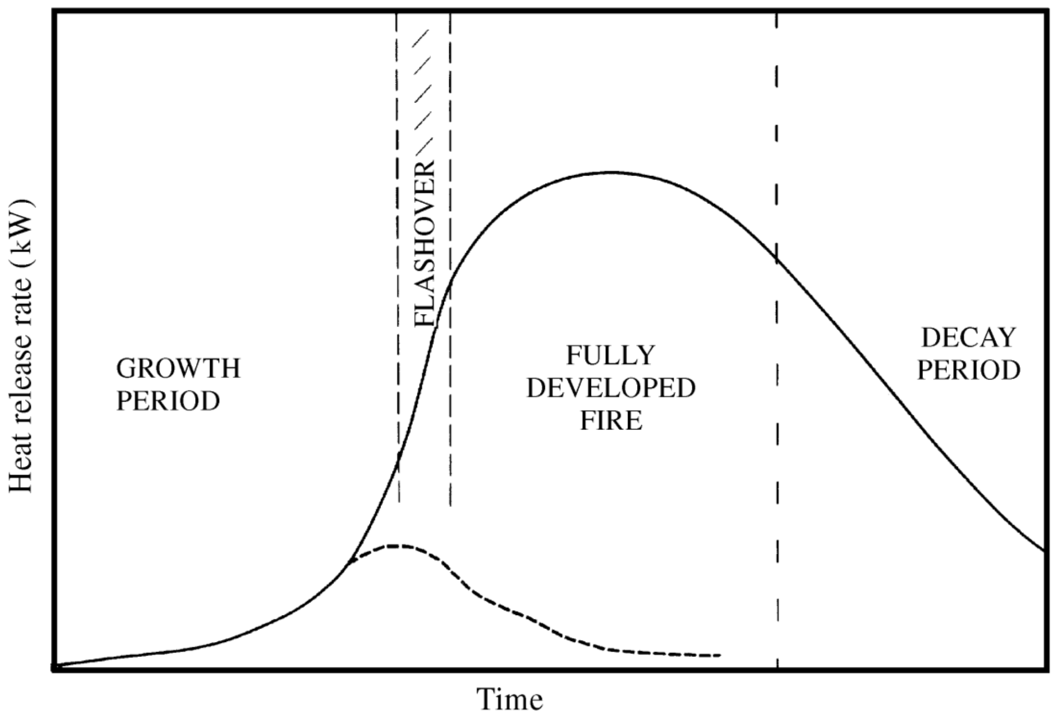
In this chapter theory regarding a building fire and especially compartment fire is reviewed. Next effects of high temperatures on concrete and its properties are disucussed. Then the definition of a Passive fire protection, firestops and their significance as a part of buildings fire safety is being discussed. Also rules and regulations concerning fire safety and fire stops are reviewed. Finally the common materials, at this time, and their usage in firestops are discussed.

2.1 Compartment fire

According to Drysdale (2011, p. 349-355) Compartment fire can be divided in five phases: Ignition, growth, flashover, fully developed fire and decay. Temperatures in ignition and growth phase are low and under 600°C. Time span of growth phase depends on the amount of burning material fueling the fire and the availability of oxygen. It is possible that compartment fire does not reach the flashover phase due to small amount of burning material or limitation in ventilation. Fire can still continue to burn for a long time and average temperature stays below 600°C.

Flashover is quick phase and occurs when temperature in sealing reaches 600°C. In this phase every combustible material in compartment ignites at the same time causing rapid temperature increase. There are also other requirements for a flashover, but they aren't important regarding the subject of study.

After flashover begins fully develop fire in which temperatures can reach as high as 1100°C. When every material capable of burning and fueling the fire is exhausted the fire reaches decay phase. What comes to time span of these phases, Flashover phase is usually really short compared to others, and temperature changes drastically in few minutes. Picture 1 shows the different phases, their time span and heat release rate involved in them.



Picture 1 Schematic drawing of the phases of compartment fire (Drysdale 2011, p. 350).

2.2 Effects of high temperatures to concrete

Before studying the interactions between concrete and firestop mastics, it’s important to understand what happens to the concrete in high temperatures. Concrete is a composite material of three or more different materials, these being normally cement, water and aggregates (Husem 2006). Depending on the desired compressive strength, proportions between these are changed, and some other binders are added.

According to Husem (2006, p. 155), reactions of concrete in high temperatures and therefore fire resistance, depend on many factors. Some of these factors are: type of aggregate and cement, the temperature, duration of exposure and moisture content of concrete. Aggregates are normally the strongest part of concrete in terms of fire resistance.

The first ingredient, which starts to react on elevated temperatures, is water. When temperature rises above the boiling point of water, evaporation of water begins. Amount of water in concrete depends on the age of concrete, water-cement ratio and the environment. If temperature rises quickly the pressure of evaporated water can cause the surface of the concrete to spall. Evaporation of water also causes rapid strength loss that can be seen before temperature reaches 200°C (Husem 2006, p. 159-160).

When temperature rises over 400°C, free calcium hydroxide starts to decompose into calcium oxide due to loss of water. If concrete is wetted again after cooling, calcium oxide can transform back into calcium hydroxide (Husem 2006, p. 155). Both OPC and HPC lose somewhat 50 % of their strength after exposure to temperatures higher than 600°C. According to experiments performed by Husem (2006, p. 160,), there are some differences between OPC and HPC at high temperatures, one of these being the possibility of explosive spalling of HPC between temperatures 300°C and 650°C OPC can also spall explosively but it is more likely for the HPC.

2.3 Passive fire protection

Before introducing the basics of fire compartmentation and firestops, it is relevant to identify the two different types of fire protection in construction. First is the concept of active fire protection. Active fire protection is by definition all means that aim to prevent the start of the fire. It usually shows in the designing of the building, materials used in structures and overall in construction. SRMK E1 also points out the importance of preventing the start of fire in chapter 4 (Ympäristöministeriö, 2011). Second is the passive fire protection, also known as PFP, which takes into account all means to prevent or slow down spreading of fire and smoke inside the building. Spreading of fire to the surroundings of building should be also prevented.

According to Aker (2008, p. 66), PFP can be divided to four main areas. First is structural fire protection, which guards the essential parts of structure from effects of fire. This can be accomplished by different kinds of protection systems like spray-on intumescent systems, gypsum-based plasters, mineral wool insulations or using concrete products to avoid the weaknesses of structural steel in fire.

Second is the compartmentation. Fire compartmentation is the basis for isolating the fire in reasonable sized spaces so that evacuation and extinguishing of fire can be done safely. Fire compartment walls and barriers protect evacuation routes from fire and smoke maximizing the time to rescue of all those who are in danger. Third main area is considered to be opening protection. This includes fire doors and windows which purpose is to maintain the protection of the fire barrier. Fire and smoke dampers, used in duct systems, are also included in this area.

The fourth area of the PFP is the main area of interest in present this study. Aker (2008, p. 67-68) defines the fourth area as firestopping materials. This includes materials used to limit fire spreading through penetrations in fire barriers. These penetrations are smaller in size than the case of the opening protection. They are mostly caused by the need of service and technical assemblies, for example ventilation, plumbing and electrical wirings, to be fed through fire barriers. As a negative effect comes the weakening of the structure. Because the penetration has to be wider than the penetrating installation, it leaves empty space in the barrier and that space can be penetrated by fire and smoke in case of fire. Therefore fire barrier loses its integrity and resistance to fire, unless something is done to the penetrations after installing necessary feed-throughs.

2.4 Firestop

There are lots of different terms describing the same or nearly the same thing in English. Other terms that can come up are for example fire seal and fire break. Firestop is a term commonly used to describe the sealing of a penetration in a fire barrier to maintain the barriers fire resistance after making the penetration. Behavior of a firestop sealant in normal conditions and at high temperatures during fire should be as stable and predictable as possible. Also the interactions between sealant and building materials should be minor and not harmful considering the fire barriers function to prevent the advancing of fire.

Firestop can be made of acrylic mastic or mortar, which seals the penetration and secures the fire barriers fire resistance. It can be also made from combination of two or more materials. For example, vertical joint in structures can be first filled with a fire foam and then covered from both sides with a fire silicone to prevent cracking of joint due to structural movements (Nullifire, 2012). There are also other products available. For pipe penetrations there are pipe collars and pipe sleeves and for larger sized holes in non-load-bearing walls it is possible to use mineral wool plates coated with fire retardant materials. There are also temporary firestop products like fire pillows or curtains to be used during the construction phase (Suomen palokatkoyhdistys ry, 2012, p. 11).

There are rules and regulations concerning fire compartments and designing of them. Some of these rules, mainly those which are dealing with firestops, are summarized next.

2.5 Rules and regulations

In this chapter the most relevant rules and regulations concerning firestops in construction are reviewed. There is a number regulations related to the fire safety, however the importance of firestops is not clearly specified in many cases. The CE-mark for construction products has become compulsory, but for some products there is still a transition phase. This is also the case for firestops which causes some confusion among designers and contractors. The following chapter addresses briefly the current situation and guides to the future of CE-marked firestop products.

2.5.1 SRMK E1 and Maankäyttö- ja rakennuslaki

Suomen Rakentamismääräyskokoelma, E1: Rakennusten paloturvallisuus and Maankäyttö- ja rakennuslaki sets the foundation for the concept of fire safety in Finland. Both contain compulsory regulations and guidelines. Both regulations and guidelines aim to guarantee the fire safety in construction.

Section 117 b § in Maankäyttö- ja rakennuslaki is dedicated to fire safety. It contains guidance and regulations of fire safety for designing and constructing of buildings. Issues addressed in this law are also described in more detail in the in SRMK. However, only the demands for buildings but no solutions of how these demands are met are described. The basic demands for fire safety in a new building are in SRMK E1 (Ympäristöministeriö, 2011. p. 4) as follows:

- Load bearing structures in building have to withstand the strains caused by a building fire for a set period of time
- Development and spreading of fire and smoke inside the building must be limited
- Spreading of fire to other buildings must be limited
- Exit from the building for everyone inside must be secured or there must be a way to rescue them otherwise
- Safety of the rescuers must be considered in construction

The effects of firestops are linked with the second and somewhat with fourth listed demand. Firstly, the spreading of fire and smoke is prevented with effective fire compartmentation. Often though, compartments are broken during service installations, which lead to penetrations in fire walls and barriers. Therefore the importance of effective fire sealing cannot be understated as a part of passive fire protection. Secondly fire compartmentation and effective sealing of penetrations ensures that fire stays restricted to a certain compartment long enough for everyone to exit the building. These two demands require to design the firestops.

Because these basic regulations do not provide sufficient information about firestops, cities and municipalities often have their own documents that address these questions in more detail. For example the Helsinki city engineer's office has published its own guidance for firestops and especially firestop plan (Rakennusvalvontavirasto, 2013). This document describes accurately the process of making a firestop plan including all responsibilities for different parties engaging in the construction process. It clarifies some regulations set in previously mentioned documents and details the information needed in making effective firestops. Important part of this document is the part, in which CE-marking and third-party certification are explained to be equivalent proofs of products usability (Rakennusvalvontavirasto, 2013, p. 1).

SRMK E1 (Ympäristöministeriö, 2011, p. 2-3) defines fire classes for different types of buildings by their size and the main intend of use. It defines also the requirements for fire compartmentation and fire resistance of used construction materials. Previously mentioned is a crucial part and must be taken into account when designing firestops. Nevertheless these rules have to be followed by the constructors at the site also.

2.5.2 CE-mark and alternatives

Purpose of CE-marking the construction products is mainly to increase and ease the market across the whole EU. CE-mark verifies that products properties are reported according to the same principles. This guarantees that every product is easily comparable to others. However, CE-mark doesn't directly indicate products quality or suitability for certain type of structures or in specific geographical locations. Temperature and moisture conditions can vary greatly with geographical location, and therefore it is impossible to determine that product which is manufactured to be used for example in southern Europe would also perform well in northern Europe.

Every product has its own instructions for use and neglecting these can easily negatively affect the products operation in the case of fire. Firestop products are usually tested and proofed for numerous different installation variations, but when they are used differently than described by technical documents it is important to consult the manufacturer. Manufacturer can give his evaluation of the intended use and possibly verify it as a functional solution to his defined extend.

As a member of EU, Finland is following the Construction product regulation (CPR). According to European Commission (2011) CPR replaced the Construction products directive (CPD), which came into force in 1988. The intend of the CPR was to simplify and clarify the existing framework and improve the transparency and effectiveness of the existing measures. Consequently, ensuring reliable information on construction products in relation to their performance by providing uniform assessment methods of the performance of construction products. However, firestop products are fairly new products compared to many other construction products and they do not have yet harmonized product standards (hEN). Lack of hEn is one reason why firestop products are in different kind of situation in regard to the CE-marking. This is confusing many designers as well as contractors in case of selecting and using firestop products.

After 1.7.2013 every product used in construction has to have CE-mark according to the CPR. However, this does not yet concern product groups that do not have the hEN, which is also the case for firestop products. For these types of products the CE-mark is not yet compulsory and the acceptability of the product can be proven otherwise. It is possible though to apply for an ETA to obtain the CE-mark.

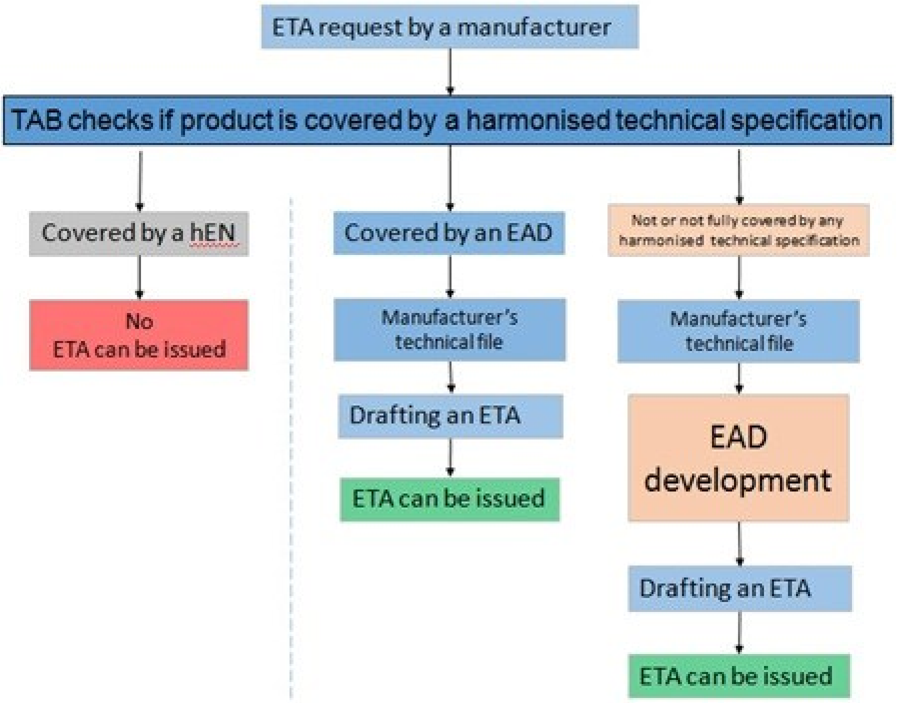
Declaration of Performance (DoP) is drawn up by manufacturer when a product covered by the hEN or the ETA is placed on the market. It provides the information about the essential characteristics of the product. Manufacturer assumes the responsibility for the conformity of the construction product with the declared performance. After DoP has been provided, CE-mark can be attached to the product. (European Commission, 2013.)

ETA is a voluntary basis for gaining a right to the CE-mark construction products. Manufacturer has to request for an ETA to initiate the process. When requesting the ETA, manufacturer has to give certain information about the product in its application. The following information is required:

- Construction products type and description, its intended use and the essential information about its characteristics and performances.
- Research or any other technical assessments results which might be helpful
- Indication if the product is not or not fully covered by a harmonised standard
- Information, if an application has been introduced to another TAB before.

Manufacturer chooses to which TAB he introduces the product. TAB has to be designated for the relevant product area. In Finland VTT Expert Services Oy is the only TAB available, but it is designated for every possible product area that can be requested for an ETA. Firestops fall in the last category or product area, which is 35: Fire stopping, fire sealing and fire protective products; fire retardant products. Application is checked by the TAB to first verify if the product is covered by the harmonised technical specification (hEN). In case, which is rather rare, when the product is already covered by the hEn, there is no possibility for the TAB to proceed in issuing ETA for manufacturer. (European Organisation for Technical Assessment, 2013.)

Next two scenarios are the most common cases: A product is covered by an EAD (or ETAG), or product is not or not fully covered by the hEn. In both cases TAB checks the manufacturer's technical file of the product and then either drafts the ETA for verification amongst other EOTA members to ensure consistency of the ETA or develops an EAD for the product. After developing EAD the TAB drafts an ETA and verifies it like in previous case. The possible paths for ETA are described in Picture 2. (European Organisation for Technical Assessment, 2013.)



Picture 2 Process of issuing ETA (European Organisation for Technical Assessment, 2013)

There is a wide debate about the CE-markings in firestop products. Because the regulations about CE-markings in firestop products differ from other construction products there are also false information passed on amongst people. This is normal in this kind of transition phase, before the hEn for firestop products is ready. After that only CE-marked firestop products are allowed in construction.

But as today, there is also one possible scenario to prove that a firestop product fulfils the necessary requirements. This is known as third-party statement, and here in Finland VTT usually gives this statement, and it is called VTT certificate. According to Rakennusvalvonta (2011), there are two policies to be considered when verifying compliance of firestop product. First policy is to use CE-marked products. Second policy is the third-party statement verifying the compliance of product in this specific case. The statement is made by a specialist, who bases his decision on the test results done by VTT and inspection of construction site. Usually VTT certificate is useful when some other specialist gives the statement, because VTT certificate proves that test are done in a accepted testing facility and following the guidelines set by ETAG 026, parts 1-3, which is the requirement for statement from other specialist than VTT. In the statement there must always be a clarification for the constancy of products properties in comparison with tests, representation of the inspection method at the construction site and a comment about products service life and necessary procedures to maintain it.

2.5.3 Firestop plan

Firestop plan is done by prime designer with other specialized designers. These specialized designers include structure, HVAC and electric designers. Firestop plan is a layout which shows the boundaries of fire compartments and their appropriate fire classes. Every firestop is marked in the layout and solution that fills the regulations is indicated. Each firestops type is also indicated in layout by letters or numbers. In detail drawing each solution is depicted with its boundary conditions, which can include allowed feed-throughs, dimensions for the penetrations, structure materials and their thicknesses and other special requirements for firestops caused by penetrations. (Rakennusvalvontavirasto, 2013; Suomen palokatkoyhdistys, 2012 p. 16.)

It is advisable, according to Rakennusvalvontavirasto (2013), to design the firestops universally, so it is possible to use products from different manufacturers and this way support the free movability of firestop products inside EU.

2.5.4 Palokatko-opas by Suomen palokatkoyhdistys ry

This booklet is not official regulation or guideline. It can be considered as an easy to understand summary of all the regulations, rules, materials and methods involving in firestopping of penetrations in fire barriers. It offers basic information regarding the subject. Booklet is good for everyone who has to work in the area of firestops all the way from designers to workers at construction sites. Suomen palokatkoyhdistys ry is the organization behind this booklet. It has been working for ten years to promote knowledge and ongoing research of firestops.

Some of the largest manufacturers and vendors of firestop products in Finland - including Hilti, Würth, 3M and tremco Illbruck - are members of this organization, and they act on their behalf honoring the goals of Suomen Palokatkoyhdistys ry.

2.5.5 Person certification for firestop installations

Person certification is possible for people who work with firestops. This certificate proves that installer has sufficient knowledge and skills needed to make an efficient firestop. To obtain a certificate one must go through two days of intense training about requirements of firestops and the installment work. Training period ends to a test, which verifies the skills of installer. Based on the training, installer gives a work sample as a proof of mastering the installment of firestop. VTT inspects this sample and upon approval issues the certificate to installer. Installer has to keep record of his installations and report them to the supervising official. If the reporting is done according to terms, the certificate holds for three years until it needs to be renewed. (Suomen palokatkoyhdistys ry, 2012, p. 14.)

2.6 Materials used in firestops

As designing and producing fire stops in construction, it is important to know the properties and behaviour of materials available for subject. Because every material has its own characteristics it is crucial to identify the variables which determine the demanded qualities for the fire stop and the sealing material.

Even if a material used in making the firestop, for example gypsum or rock wool, is qualified for this kind of usage, it can not in most cases by itself work as a proper fire stop if the joining seal with surrounding structure is not good enough to withstand the heat and gases in a case of fire. This chapter introduces some basic information about the most common and used products in firestops in Finland.

2.6.1 Acrylic-based mastics

Acrylic-based mastics are mostly used as a fire and acoustic seal in structure joints, because acrylics are smoke- and waterproof. Acrylic mastics are incombustible and elastic. Usually elasticity of acrylics is around 10 %. Acrylics are often used in combination with other fire stopping methods as a finishing layer due to fact that they can be painted after drying. (Suomen Palokatkoyhdistys ry, 2012, p. 10.)

Other benefit of using acrylic mastics is their intumescent ability at high temperature. When temperature rises high enough, usually around 250°C, acrylic mastics start to expand and therefore seal the joint even tighter than before. Even though acrylics expand in high temperatures, expansion is not sufficient to compensate for melting of plastic pipes.

Consequently, acrylics are used normally in penetrations consisting of metal pipes or cables (Würth Oy, 2014, p. 7; Nullifire, 2011a).

2.6.2 Silicone-based (elastic) mastics

Reasons for using different kinds of silicone mastics to seal penetrations in fire compartments are usually defined by the nature of silicone. Mastics based on silicone, in most cases, have similar properties regardless of manufacturer or manufacturing process. According to de Buyl (2001), degradation of silicones starts usually in higher temperatures than 400˚C, are non-flammable, non-combustible and have a low thermal-conductivity as well as a high thermal stability. Silicones are also usually resistant to water and mold after curing. Consequently, the field of their application is wider field in comparision with for example acrylics. According to Suomen Palokatkoyhdistys ry (2012, p. 10), silicone is well resistant to UV-light and ozone so it is well suitable for outdoor use.

There are also some negative properties of silicone, for example they cannot be painted and they do not expand in case of fire. Consequently, silicones are not effective when used as seals of penetrations with plastic pipes or any other installation that does not retain its measurements at high temperature. The silicon is the best alternative for structural joints in which some movement occurs. The elasticity of silicone mastics can be up to 25 % depending of the specific product. (Suomen Palokatkoyhdistys, 201, p. 10.)

2.6.3 Intumescent (Graphite-based) mastics

Intumescent mastics are good solution especially for penetrations consisting of PVC-, PE-, PP-pipes or other materials which are not very well resistant to fire. In the case of fire these types of materials will burn, melt, or deform already at relatively low temperatures. When the Intumescent mastics are exposed to high temperature and flames they expand and produce char which fill up the space left by the melting pipes. This char prevents the flames and gases to flow through the penetration. It also prevents the heat conduction. Intumescent mastics consisting of vermicular graphite start to react at temperatures of over 150˚C and their volume can be multiplied up to 7 times (Suomen Palokatkoyhdistys ry, 2012, p. 10; Horacek & Pieh, 2000, p. 1110).

Intumescent mastic can be used to replace pipe wraps in some solutions, but this is not possible for pipes having large diameter. According to Nullifire (2011c) and Würth Oy (2014, p. 11), plastic pipes having a diameter of up to 90 mm of can be sealed in penetration with intumescent mastic if the hole size meets the requirements.

2.6.4 Polyurethane fire foams

Polyurethane foam is probably the easiest sealant type to use in firestops. Even though being easy and widely used, it does not have the intumescent ability like acrylic or graphite materials. Thus it is not effective in sealing penetrations consisting of plastic pipes or electric wires which melt at high temperatures leaving empty spaces in penetration. (Suomen Palokatkoyhdistys, 2012, p. 10.)

Foams are suitable for joints and penetrations with little expected structural movement. Best results with fire foam can be achieved when used in combination with for example acrylic mastics. In thick joints inner part of the joint is filled with PU-foam and then filled to the surface of structure with other mastics, like acrylic or silicone. (Nullifire, 2012).

2.6.5 Gypsum-based mastics or mortars

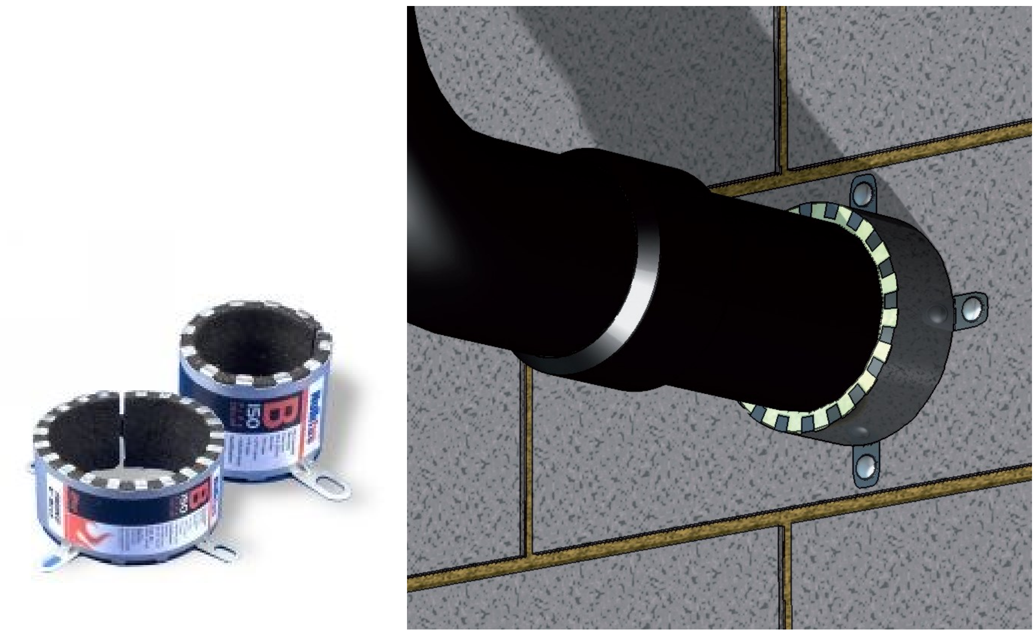
Gypsum has been known to be an effective barrier against fire. It is non-combustible and it effectively constrains fire. This is because of the fact that gypsum has water bonded in its chemical structure. Therefore in a case of fire, the water starts to evaporate from the side of gypsum which is exposed to fire and at the same time the other side is still relatively cool. Because water is heating and boiling it causes the gypsum to crack. Cracking accelerates the destruction of gypsum and temperature rise on the other side. (Mahendran & Keerthan, 2012, p. 105.)

Gypsum is cheap material and easy to use for filling large areas in walls and floors. Firestop gypsum is designed to endure high temperatures and its properties are refined for using as a firestop or as a part of firestop system. Mixing process is easy, because only water is needed to ne added. A gypsum mortar is usually easy to cast as it is flowable and does not need any compaction. It is often used to reduce the size of penetration before using other firestop mastics.

2.6.6 Pipe wraps, collars and sleeves

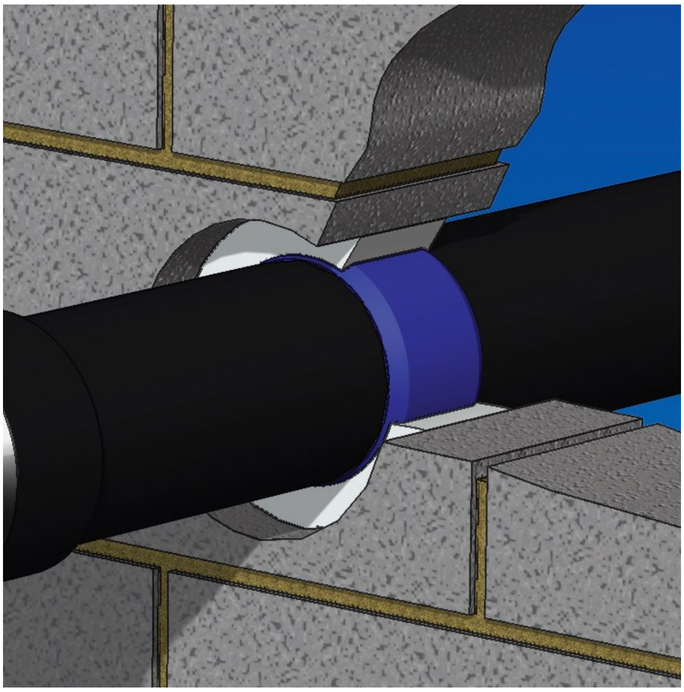
Pipe wraps, collars and sleeves will be treated as one in this part, because they all share the same principle of intumescence. All elements are installed around a pipe either inside or outside of the penetration in structure. They are usually used for larger diameter pipes which are penetrating the structure at different points away from each other. Because the diameter of pipe in these cases is large, it is very hard to make an effective firestop using only intumescent mastics described earlier. There is just not enough space between the pipe and the structure to fill up with sufficient amount of mastic to expand and tighten the penetration in case of fire.

Pipe collar is installed outside the penetration around the penetrating pipe (Picture 3). Collar is then anchored to the surface of the structure. Pipe collar has a metal frame restricting the expansion of intumescent material and forcing it to seal the opening in case of fire. This installation method leaves some free movement inside the penetrated structure for the pipe, which is important if pipe is fragile and can be easily damaged by the structure movements.



Picture 3 FP150 Pipe collar (Nullifire, 2011g)

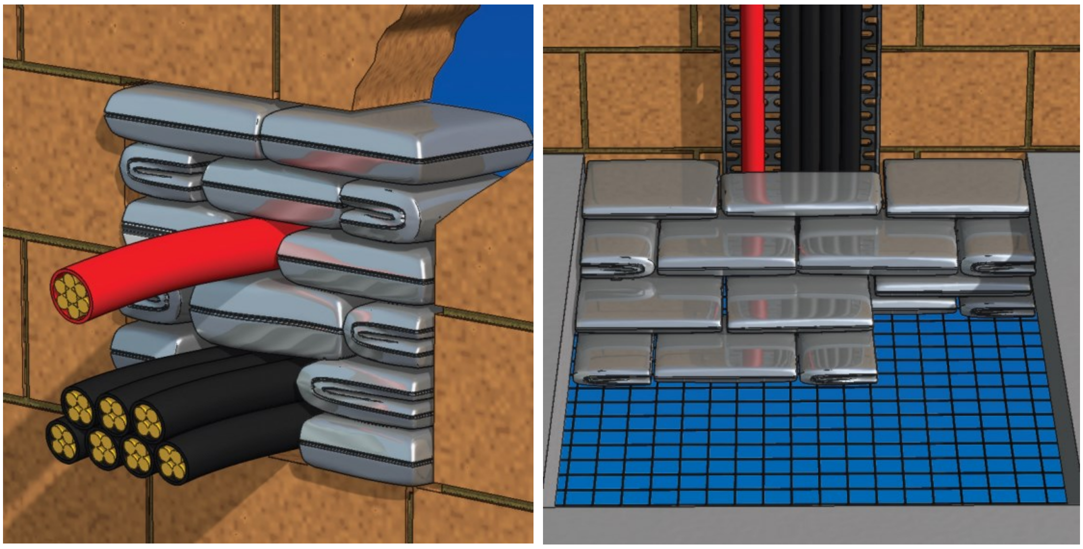
Pipe wrap is attached to the pipe itself inside the structure and the joint is then sealed with firestop mastic (Picture 4). Pipe wrap is also made of intumescent material, but it does not have metal frame to restrict the expansion, and therefore wraps are used inside the penetrated structures. (Nullifire, 2011h.)



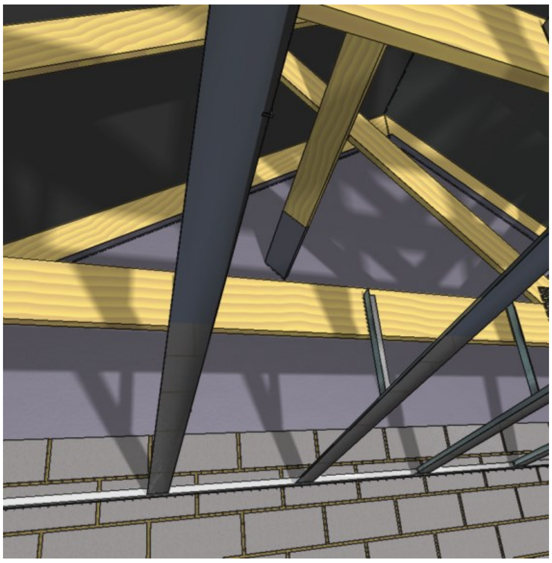
Picture 4 FP300 Pipe wrap (Nullifire, 2011h)

2.6.7 Firestop bags, pillows and curtains

These products are made of fire resistant materials and are normally used as temporary firestop during construction. They are suitable for spaces in which protection from dust, noise or other restrain is needed. One good use for bags and pillows are installations that are altered in short periods and permanent fire protection would be expensive to use. Bags and pillows can also be used for permanent firestop seal in combination with other materials. In Picture 5 firestop bags are used both in floor and wall penetrations. Fire curtains can be used to cover large openings in ceilings, as in Picture 6. (Nullifire, 2011f; Nullifire 2011i.)



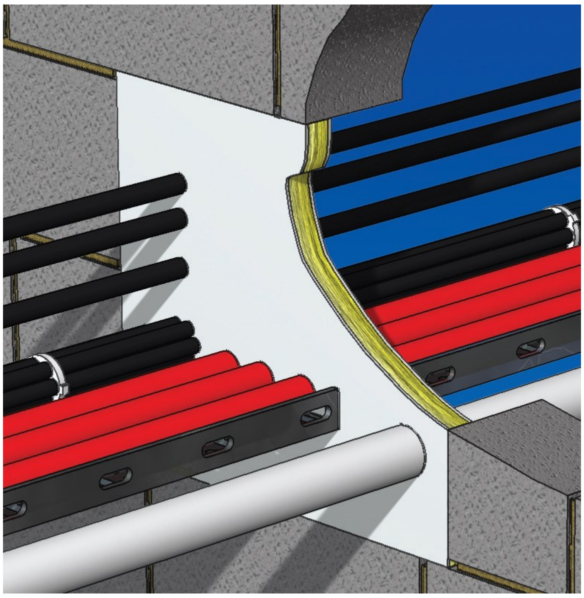
Picture 5 Firestop bags (Nullifire. 2011f)



Picture 6 Firestop curtain (Nullifire, 2011i)

2.6.8 Coated mineral wool batt

For non-load bearing penetrations there are also specially designed mineral wool fibre plates available (Picture 7). These plates are coated with material that can endure the heat and smoke coming from fire. Seal of the batt and surrounding material must be secured with appropriate firestop mastic after installation.



Picture 7 Coated mineral wool batt (Nullifire, 2011e)

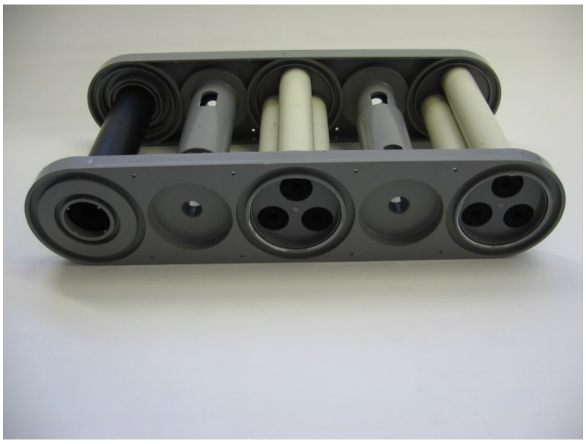
2.6.9 Mineral wool and steel plates

The most basic, well-known, and in early days of firestops, easiest way to make an effective sealing was a combination of dense rock wool and steel plates. The seal between penetration in structure and penetrating installations was compacted with rock wool and then steel plates were installed on both sides of penetrated structure. This fire stop method has been widely used in Finland to this date. Standards (SFS 4919, SFS 4920, SFS 4922) advicing use of this have been repealed but RT 80-10238 is still available without any mention about repealed standards, which it is based on. Compared to previously mentioned and described methods and materials, this is considered to be less effective and it is often hard to implement because of tight working areas and small empty space between feed-through and the hole in structure. (Pylkkänen, 2010. P. 44.)

2.6.10 Modular firestops

When buildings are constructed using elements, it is possible for the manufacturer of the element to prepare penetrations during the manufacture of element following the demands of constructor. In this case the industrial penetration ready products are used. These products are designed to seal the penetration to withstand fire without other firestop products. They are usually combined from different materials, for example steel and different types of rubbers as in Roxtecs system in Picture 9. After the pipes or cables have been installed some sealing is usually needed mainly for acoustic reasons. (Suomen palokatkoyhdistys ry, 2012, p. 11-13.)

There are also products that can be installed at the site during or after the casting of concrete. These products have specific needs for the penetration diameter. Done either way, this shortens the time needed in the construction site to seal the penetrations. There are no need to schedule many different workers to work at the same place, because modular firestop systems ensure easy feed through of cables and pipes without need of firestop sealants. It is also possible to have reservations for future additions. Picture 8 shows product, which can be installed during casting in-situ, or in concrete element factory. (Sewatek Oy, 2014; Roxtec International AB, 2014.)



Picture 8 Modular firestop system for cable penetrations (Sewatek Oy, 2014)

Picture 9 Modular firestop system from Roxtec Oy (Roxtec International AB, 2014)

2.7 Interaction between concrete and sealant materials

Literature discussing firestops, is mainly concentrated on the fire resistancy of firestop material. Fire tests are done to examine how the mastic works at high temperatures in terms of integrity and insulation. However the effects on concrete or the interaction between concrete and firestop mastics its not studied more closely. The main purpose of firestop materials, including sealant mastics as well as other products, is to maintain fire barriers integrity and resistance in the case of fire. Therefore, it is important that possible reactions between mastics and different construction materials are known. At the best, the reactions should support the fire resistance of structure and in no case should they weaken it.

Liu and Wu (2011, p. 1840-1841) found out that silicone rubber sealant has good bond strength with concrete. Furthermore depending on the pretreatment of concrete surface the bond strength can be increased from 0,11 MPa to 0,53 MPa. They found out also from SEM examination, that silicone rubber sealant left residues on the surface, which was firmly covered by this residual silicone sealant.

Closer study should be performed on the interactions between concrete and firestop sealant mastics to achieve better knowledge on how different materials used in sealants function with concrete.

3 Case studies

In this chapter some cases of building fires will be discussed. The main purpose is to study the importance of firestops in the case of fire. The first described case had improper firestops. In the second case fire compartmentation and firestops were working efficiently, thus minimizing the danger and damages.

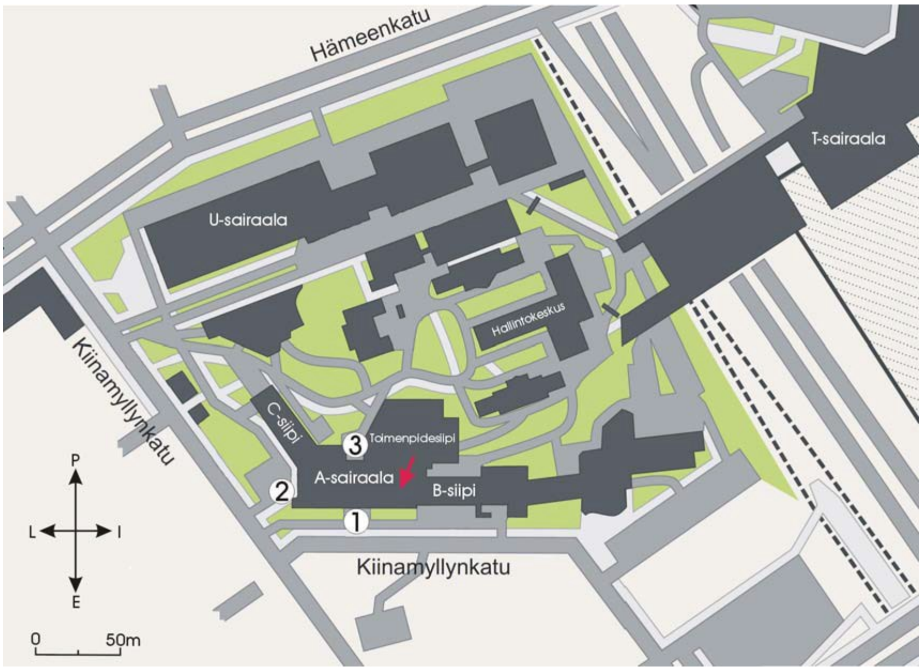
3.1 Fire in A-wing of TYKS in 2.9.2011

In November 2011 headlines of newspapers got filled up with news about fire in hospital in Turku. TYKS, which stands for Turun Yliopistollinen Keskussairaala was the hospital that had dangerous fire. Facility is one of the largest hospitals in Finland, and has 3013 staff members and 803 sickbeds (TYKS, 2013). TYKS consists of three separate parts: T-hospital, U-hospital and complex of A-, B-, C-wings and operation-wing (Picture 11). Fire started in A-wing so the following deals only with the properties of A-wing unless mentioned otherwise. Onnettomuustutkintakeskus conducted inclusive accident study and documented results in a report. According to the report 176 patient and 56 people of staff were evacuated from the building during the fire. There was no need to evacuate patients from ER, so 11 patients stayed at the hospital until fire department extinguished the fire. Summarizing there was total of 187 people in the building when first detection of fire was made. (Onnettomuustutkintakeskus, 2012. p. 9, 15).

The building is constructed in 1937. Renovation for basement through third floor was done in 1981 except for the ward which was renovated later. In 1995-1997 floors from three to eight were renovated and during renovation every floor was divided to two different fire compartments. By modern standards buildings fire class is considered as P1, which means that building has to survive full scale fire without collapsing. Walls in fire compartments are designed as EI190, which stands for compactness and insulation for 190 minutes in the case of fire. (Onnettomuustutkintakeskus, 2012. p. 34; Ympäristöministeriö, 2011. p. 6-7.)

In this case the fire started in the suspended ceiling, on the 2nd floor of A-hospital (Picture 11). Probable cause for fire was electrical malfunction in the nurse-calling system, whose main unit was located inside suspended ceiling. Therefore the fire couldn't be detected directly from the flames. First detection of fire was because of smoke started to develop and come through the ceiling in the corridor, where it was first noticed by nurses. However the precise spot of fire was not detectable. In the upper floors there were fire alarms from the alarm system, but these were first neglected due to large number of false alarms during summer. Fast spreading of smoke and fire can be seen from surveillance footage in Picture 10. Time span between the first sighting of the fire in screen C and corridor filling up with smoke in screen H is under two minutes.

Picture 10 Pictures taken from surveillance camera video on 2nd floor (Onnettomuustutkintakeskus 2012. p.13)



Picture 11 TYKS Area, arrow indicates the fire starting point (Onnettomuustutkintakeskus, 2012. p.11)

It is clearly stated in the report that insufficient fire stops were reasons for fast spreading of fire, combustion gases and smoke through fire compartments. Fire compartmentation was designed correctly and efficiently following regulations at the construction time of the building. Fire compartmentation worked well in the third floor and kept patients in the ER safe. On the other hand firestops weren't done correctly or there were no firestop at all in some parts of the building. Biggest lack of fire stops was inside the suspended ceiling over the fireproof doors. In this case these fire-stops would have functioned as smoke barriers, because the second floor had only one fire compartment (Onnettomuustutkintakeskus, 2012. p. 57). Mainly there were places where the feed-throughs in walls were poorly sealed or not sealed at all. Secondly there were places where there was no wall at all inside the suspended sealing above fireproof doors. This basically created vertical chimney effect and in conjunction with leaks from oxygen pipes fuelled the ongoing fire. (Onnettomuustutkintakeskus, 2012. P. 56-57, 61.)

Combustion gases were the most dangerous element in this case. Because suspended sealing didn’t have effective firestops, the gases flew inside the sealing virtually everywhere in the floor and even to upper floors. The ventilation was also one way for the gases to travel as the ventilation pipes weren't perfectly sealed at every joint. There was also confusion about shutting down the ventilation system among the staff (Onnettomuustutkintakeskus, 2012. p. 61). Situation wouldn’t have been so severe if the fire had started in some of the upper floors. The floors below the fire wouldn’t have been in immediate danger. Second floor was maybe the worst possible floor in this case because that led to a danger in every upper floor also. The fast spreading of smoke and gases can be clearly seen below in Picture 10.

Every floor should be treated as a different fire compartment according to SRMK E1 (Ympäristöministeriö, 2011. p. 6). In this case flames as well as gases had free access to upper floors through an unsealed cable feed-through from second floor to third floor. Smoke advanced also to first floor through the same feed-through. It isn't mentioned in the report how these penetrations through fire compartments were designed, thus it is impossible to determine was the design precise enough about tightening the penetrations. Nevertheless report doesn’t tell was it predetermined who was responsible for penetrations. There is always possibility that fire compartments had been designed inadequately, but because this case concerns hospital building, which has tightest regulations of fire safety, we can assume that designer was aware and capable of such design. More likely the sealing was done negligently by the workers during construction.

Finally, whatever the reason, previously mentioned lead to a failing fire compartmentation and made the extinguishing of fire and the evacuation process hard for the fire department. Assumptions of the spreading of fire were made presuming that compartments were working as they should have. Therefore fire fighters had no idea how broadly the flames and gases would roam in the building before entering it. Even though after entering the building firemen examined the upper floors, but they weren't still really aware how widely the fire had spread before they actually started to extinguish it. (Onnettomuustutkintakeskus, 2012. p. 59-61.)

Luckily, because of fast reaction of staff, there were no casualties even though fire was advancing exceptionally aggressive and hence had all potential to be disastrous. Staff isolated the part of the floor where the smoke was detected first. This was right call. Despite smoke and combustion gases got through designed fire compartments inside suspended ceiling, because space above fire-doors wasn't properly sealed. Hence closing the fire-doors had little effect in isolating the fire. If the fire compartmentation would have been done correctly and the penetrations would have been sealed efficiently the fire had never reached the other end of the second floor nor the third floor.

In inspections, made before the accident, there were no complaints given about fire compartmentation or firestops (Onnettomuustutkintakeskus, 2012. p. 47). This leads to thinking about fire inspections strictness. Usually most common complaints in fire safety inspections concern about safe exit from the building. These are easily visually detected during a simple walk in the building. By contrast, firestops are usually hidden in the technical spaces in the ceilings, walls or floors, and are therefore impossible to observe without tearing down some surface structures.

3.2 Hotel Fire in Kuhmoinen 23.12.1995

Fire in Hotel Eurooppa 4 in Kuhmoinen was one of the biggest incidents on year 1995. The fire lead to one death and many injured during escape from building and helping others to escape. This case had potential to be even more disastrous, but because fire compartmentation was done in some part of the building properly, people were able to get to safety. This is positive because in many other aspect of fire safety there were lacks and negligence, which could have led to larger number of casualties and even larger property damage.

In the time of accident hotel was mostly occupied by Russian tourists, of which many were children. In total there were two groups of people. First one consisted of 34 school-children and 11 adults. Second group consisted of 19 adults. In addition to previously mentioned there were also about 10 other people staying at the hotel during the night of the accident.

Building was constructed in 1966 and since then total of 3 extensions or renovation jobs have been conducted. Old part of the building was extended first in 1971 and later in 1975 with a restaurant part. New two-storey part, containing accommodation, saunas and meeting rooms, was constructed in 1975. Renovation was started in 1995 and was still incomplete when the fire started. (Onnettomuustutkintakeskus, 1998. p. 16.)

Building was divided to four different fire compartments (Picture 12). In addition staircase and basement floors were also separate fire compartments. Before the repairs building was verified to fulfil the fire safety requirements of its time, being classified as an E-class building, which by modern standards in SRMK E1 can be treated as P3-class building. However building had materials and structure solutions which of some were better and some worse than C-class.

Cushion on the seats of dining booths was highly flammable foam plastic, and it was plentiful in the restaurant part. According to Sisäasiainministeriö (1984), materials used in accomodation facilities, including hotels, must be classified to ignitability class SL1, which stands for fire resistant or difficult to ignite. VTT did research on the materials used in cushions and dining booths and the results proved that neither cushions nor the lining did not meet the requirement of ignitability class SL1. set for this kind of building. Amount of combustible materials was highly increased by using chipboards and polyurethane cushions in seating. Overall the old part of the hotel did not meet even the lowest P3-class in terms of modern fire safety regulations. (Onnettomuustutkintakeskus, 1998, p. 23.)

Picture 12 Fire compartmentation of the upper floor in hotel

New accommodation part was separate fire compartment and both of its floors were own compartment as well. Its main building material was stone and walls and floors met the A 60-class requirement. New part had also its own electric system which didn't interact with the system in old parts. Also ventilation and water systems were separate from the old part. This fact leads to a conclusion that there were very few penetrations in fire compartment wall between the old and the new part. (Onnettomuustutkintakeskus, 1998. p. 17.)

According to accident research report by Onnettomuustutkintakeskus (1995, p. 70), one of the reasons for fast progression of the fire was in open position left fire-doors. Thus fire advanced very fast from restaurant to the old accommodation part of the hotel. Moreover smoke and toxic combustion gases spread through the old part to the second floor of the new part of the hotel.

Sisäasiainministeriö has given regulations concerning fire safety in hotel and catering related buildings. In this case hotel Eurooppa 4 is clearly this kind of building. According to this regulation in a hotel room there must be instructions for actions in case of fire or accident. These instructions must have the information about emergency telephone number, address of the hotel, telephone number of the hotel, location of the nearest telephone and directions to follow in case of a fire. Nothing of this information was available in hotel rooms. (Onnettomuustutkintakeskus, 1998. p. 18.)

Regulations also demand installing of fire detectors in hotel rooms, if there isn't automatic fire-alarm system in the hotel. These fire detectors must meet the requirements set in guideline given by Sisäasiainministeriö (Palovaroittimen, palovaroitinryhmän ja –järjestelmän teknillisistä ominaisuuksista ja toiminnasta annettu ohje 7/011/93, 1993). Fire detectors had been acquired but they were never installed before the fire. Lack of fire detectors in hotel rooms was acknowledged in fire inspections, but was never officially documented. Moreover VTT (Valtion Tieteellinen Tutkintakeskus) conducted tests for the fire detectors retrieved from building. Results in these tests suggest that fire detectors did not meet the regulations in every aspect. (Onnettomuustutkintakeskus, 1998. p. 19.)

4 Summary of literature review

The two described cases showed how crucial for fire safety is effective sealing in penetrations through fire compartments is. Application of modern technology and products is in most cases very easy. However, in many cases firestops are often just made to look good and to pass through the inspections to save money. Unfortunately, such approach can lead to human casualties.

Construction inspections play a major role to prevent such negligence. Some hidden areas are often left unchecked and do not follow any recommendations and codes. Therefore, it is important to make sure that these structures are also done in accordance with regulations. In some cases the constructor might not have been even fully aware of different, often better, solutions. Unfortunately, in construction business it is common to look previous cases saying that “This has been always done this way”. Of course, there is nothing wrong with this approach when everything was the same, but regulations and demands change over time. The best approach is always to consult fireproofing experts. The firestops are expected to last the whole life cycle of the building, but they may also need maintenance. Maintenance program for firestops should be always made at least in buildings which consist of many fire compartments.

Onnettomuustutkintakeskus has conducted and documented thoroughly many cases of building fires in last two decades. Unfortunately, the written reports concentrate mainly on actions of people and rescuers before and during the fire. Some not very detailed studies of buildings fire safety were also included. In general, it appeared that well done fire compartmentation and effective firestops restricted spreading of smoke and gases and enabled evacuation of people. In the opposite, lack of fire compartmentation or not properly done fire compartmentation resulted in human casualties.

First case is a good example of what happens or could happen if a fire compartmentation and more in detail firestops fail. When these two parts meet the conditions given by regulations, building fire doesn't often end up in news. Usually effective fire compartmentation guarantees a safe exit for the people inside building as well as safe conditions for fire department to put out the fire. All though in this case there were no casualties as a sum of good conditions, fast reactions and a bit of luck.

Second case is an accident in which there isn’t any reason to doubt malfunction in firestops or in fire compartmentation. Moreover the functionality of firestops didn’t have considerable effect in the fire. Nevertheless in this case there were casualties, but the reason was in wrong actions and decisions of people in dangerous situation. Despite, casualties were significantly lower than what they could have been without proper implementation of fire safety aspects.

Firestop materials have been studied and developed for decades. At present there are many good materials available and many solutions exists for different types of need. Companies offering firestop materials usually have designs showing how to use their products efficiently in sealing the penetration. Products have also guidelines regarding the penetration holes sizes and empty space between pipes and the hole. Manufactureres have also tables showing different sizes for sealing thickness and how much time the firestop withstands the fire without losing its properties. With this knowledge it is certain to state that the reason for a failing firestop is rarely the firestop material itself, but merely the result of poor workmanship.

Firestop materials are normally tested in fire tests, in which by burning some fuel firestop is exposed to heat and flames. The importance in these tests is how the firestop material behaves in the first 30 to 180 minutes of fire and if it does restrain the spreading of fire and from advancing through the fire barrier. However no closer study were conducted on how a firestop material interacts with other materials, for example concrete or plastic. The experimental part of the present study examines the behavior interaction between concrete and firestop mastics during exposure to high temperatures in heating oven.

5 Experimental work

Buildings behavior in fire should be predictable in order to enable safe evacuation of people and effective extinguishing of fire. Depending on materials used in construction, this behavior can be somewhat different. Today it is no problem to construct buildings in such way that they can withstand exposure to high temperatures as well as flames for long times. However, usually long times are not needed for evacuation because toxic combustion gases are the limiting factor in saving human lives. This is the part in which firestops are some of the most important aspect.

Nowadays there is a large number of different firestopping products availble for different kinds of penetrations in fire barriers. Some of them have CE-mark as a proof of quality, and others have other types of approvals and certifications. Experimental study of this thesis include tests with various types of firestopping materials and their behavior in combination eith normal and high strength concrete at three different temperatures.

The main objectives of the experimental studies are:

- Does the adhesion between different materials and two types of concrete alter before and after heating
- Effects of temperature and presence of sealants on the concrete microstructure
- Effects of concrete type on behavior at high temperatures and in combination with the firestop mastics
- How does non-fireproofed sealant mastic perform comparing to other mastics?

5.1 Materials and test parameters

Five different sealant mastics were chosen for this study. Four of which are firestop mastics and one is M1-classified structural joint sealant mastic. First mastic was acrylic-based mastic, FS701. Second mastic was silicone-based mastic, FS703. Third mastic was graphite-based intumescent mastic, FS705. Fourth mastic was gypsum mortar, FR220. Fifth mastic was hybridpolymer mastic, SP525. Last mentioned, SP525, is not firestop mastic, and it is not supposed to be used in any fireproof instalment. It is designed to be used in structural joints inside buildings due to its M1-classification, which stands for low emission of TVOC, HCOH, NH3, carcinogens and odours (Rakennustieto, 2010).

Concretes are manufactured using cement, aggregates, other binders and additives available at Aalto university concrete laboratory. Firestop mastics are from same manufacturer, tremco Illbruck.

Materials, concretes and their combinations tested are listed in Table 1.

Table 1 Test sample combinations

	Normal concrete, 13.1. N				High strength concrete, 15.1. H			
	150x150			100x100	150x150			100x100
	low temp (300 Celsius)	high temp (700 Celsius)	reference	Compress strength	low temp (300 Celsius)	high temp (700 Celsius)	reference	Compress strength
FS 701 (acrylic)	N 701 A	N 701 B	N 701 C		H 701 A	H 701 B	N 701 C	
FS 703 (silicone)	N 703 A	N 703 B	N 703 C		H 703 A	H 703 B	N 703 C	
FS 705 (graphite)	N 705 A	N 705 B	N 705 C		H 705 A	H 705 B	N 705 C	
FR 220 (gypsum)	N 220 A	N 220 B	N 220 C		H 220 A	H 220 B	H 220 C	
SP 525 (normal sealant, not fireproofed)	N 525 A	N 525 B	N 525 C		H 525 A	H 525 B	N 525 C	
reference cubes				N1				H1
				N2				H2
				N3				H3
Total of samples	15			3	15			3

Lower temperature simulates compartment fire in ignition and growth phase, in which heat and combustion gases affect the firestop and concrete. In this phase the air tightness of firestop is most important factor. For compartment fire it is possible that the temperature stays for long time below the temperature needed for the flashover. This usually involves inadequate ventilation in the compartment, so that fire doesn't have enough oxygen to grow (Drysdale 2011, p. 351-352). What comes to saving human lives in case of fire, it usually is possible only before flashover when temperatures are lower and the deadliest factor are combustion gases generated by the fire (Drysdale 2011, p. 378).

Other scenario uses higher temperature and is closer to a fully developed fire after flashover phase. One restriction to choosing the higher temperature came from the effects of high temperatures on concrete. It was not intended to use too high temperature, which would have caused the concrete to deteriorate too much for experiments done after heating. Other restricting fact was the ovens power and times involved in reaching and maintaining higher temperatures. As stated later, exposure time to temperatures over 200°C - when exposure to maximum temperature of 800°C was one hour - was over 7,5 hours. This alone goes well beyond the durability design of firestops.

After taking all this into consideration, lower temperature was set to 200°C and higher to 800°C. Exposure time for both temperatures were set to one hour disregarding the time needed to reach desired temperature. Scenario involving the maximum temperature of 200°C can be discussed as a situation where fire hasn't taken over the whole compartment, is limited by available oxygen or burning material and there isn't really serious damage occurred to the fire barrier and firestop. Scenario of 800°C as a maximum temperature can be viewed as a compartment demolished completely beyond repair by the fire.

Interest in the study was in the behaviour of concrete and fire mastics as a separate material and also in reactions between them, so the long exposure time was not considered to be a major problem. It restricts, however, how we can interpret the results in the terms of fire safety or products performance in fire.

5.2 Equipment

In this chapter equipment used in experimental work is introduced mainly with brief descriptions and with pictures.

Concrete mixing machine: Pan type concrete mixer.

Picture 13 Concrete mixer

Air mass meter: similar as addressed in EN 12350-7 for pressure method.

Slump test equipment: Cone, bottom plate and rod addressed in EN 12350-2.

Compression strength test machine: Toni Technik, Processor B. Ranges 50 – 2000 kN.

Picture 14 Compression strength testing machine and test sample ready to be tested

Concrete saw: Rotary table saw with a diamond blade and water cooling.

Concrete drill: Bench type drilling machine with diamond drill and water cooling.

5.3 Concrete mix design

When designing concrete mixes the highest priority was to design to mixes that have properties varying from each other. Most important properties relative to the study were set to be the water/binder-ratio and the compressive strength. Normal strength (K35) concrete and high strength (K80) concrete fulfilled these properties.

Two different types of concrete mixtures were used in these experiments. First mix was designed as K35 concrete with normal Portland cement as binder. This mix is referred later as OPC, Ordinary Portland Concrete. Second concrete mix was high strength concrete designed as K80 and will be referred later as HPC, High-Performance Concrete. Proportionings of concrete mixes are presented in Table 2. Because the study concentrated on the behavior of firestop mastics in combination with concrete at high temperatures, properties of fresh concrete were of minor importance. Therefore requirements for fresh concrete were good workability and no segregation of substances.

Table 2 Proportionings of concrete mixes.

	OPC	HPC
Sement type	CEM I 42,5 N	CEM I 52,5 R
Sement amount [kg/m^3]	300	400
Aggregate amount [kg/m^3]	1818	1859,2
Silica fume [kg/m^3]	-	28
Super plasticizer (VB-Parmix) [kg/m^3]	0,5	5,35
Water [kg/m^3]	195,3	143,8
Water-cement-ratio	0,64	0,35

Concrete mixes were made on two separate days and both were mixed using Pan type concrete mixer. First the aggregates and binders were weighted and placed in the mixer and mixed together by hand using spattle. No dry mixing was done before adding water. First all ingredients, except superplastizicer (VB-Parmix) were mixed for one minute. Then, still continuing the mixing process, VB-Parmix was added. Due to a very small amount of super plasticizer, it was first mixed with 0,2 litres of water, to make sure it got mixed well enough with the other ingredients after adding.

After mixing, fresh concrete was measured for air content (SFS-EN 12350-7), density and workability (SFS-EN 12350-2) (Picture 15). Test results proved that requirements were met. Results from tests can be found below in Table 3.

Table 3 Results of the tests for fresh concrete mixes

	Slump [cm]	Air content [%]	Mass [kg/0,008 m^3]	Calculated density [kg/m^3]
OPC	9	2.3	18.83	2353.75
HPC	4.5	2.9	19.24	2405

Picture 15 Fresh OPC mix after slump test

5.4 Sealant mastics

Basic properties of firestop sealants used in experimental study are discussed briefly in this chapter.

5.4.1 FS701 acrylic mastic

According to Nullifire (2011a) FS701 is fireproof acrylic emulsion based sealant mastic. It is usable indoors in fireproofed structures and joints with little structural movement. It can be used in combination of following materials: concrete, wood and steel. Also usage in fire barrier penetrations including pipes is possible. No special preparation of surfaces is needed, only cleaning of surfaces from dust and other loose material is adviced. Fire resistance depends on materials, but varies from EI90 to EI300.

5.4.2 FS703 silicone mastic

FS703 is elastic silicone based sealant mastic suitable for both indoor and outdoor installations. Possible materials are the same as for FS701. Achievable fire resistance classes are same as for FS701. Flashpoint for FS703 is 100°C. (Nullifire, 2011b.)

5.4.3 FS705 intumescent mastic

FS705 is graphite based intumescent sealant mastic, which can be used in pipe penetration to replace fire collar. In the case of fire, mastic expands and seals the pipe penetrations preventing the spread of fire and smoke through penetration for up to two hours. When using FS705 the penetration size and pipe size has to be in certain limits to secure the proper functioning of mastic. Also exposure to water or excessive moisture has to be prevented during installation and curing. Hence, moisture damages the mastic and its properties. (Nullifire, 2011c.)

5.4.4 FR220 gypsum mortar

According to Nullifire (2011d), FR220 is gypsum based, unshrinkable and lightweight firestop mastic. It can be used in various feed-through assemblies consisting of aluminium and copper cables, steel and copper pipes and ventilation ducts and shafts. Before applying the mastic, all porous surfaces must be watered and all casting molds must be installed. The mixed mass starts to settle and dry after 10-20 minutes, and it will harden after 30-90 minutes, depending on the water content of mass. Compression strength of hardened FR220 is between 7 and 10 MPa, so it can be used also in cases which require load bearing capabilities.

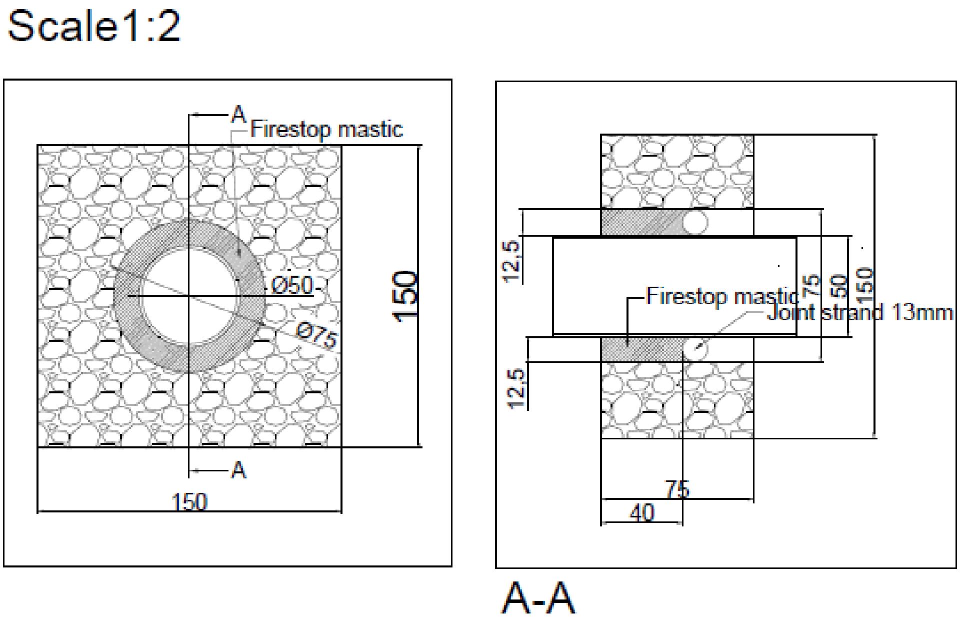
5.4.5 SP525 sealant mastic

SP525 is hybridpolymer sealant mastic, which is intend to be used indoors and outdoors for façade and structure joints. It is M1-classified mastic usable with every usual construction material. It is not fireproof mastic, like all others used in experimental study. It is durable in temperatures between -40°C and 90°C. When applying to porous materials, for example concrete, brick or masonry, priming with special primer is recommended.

5.5 Test samples

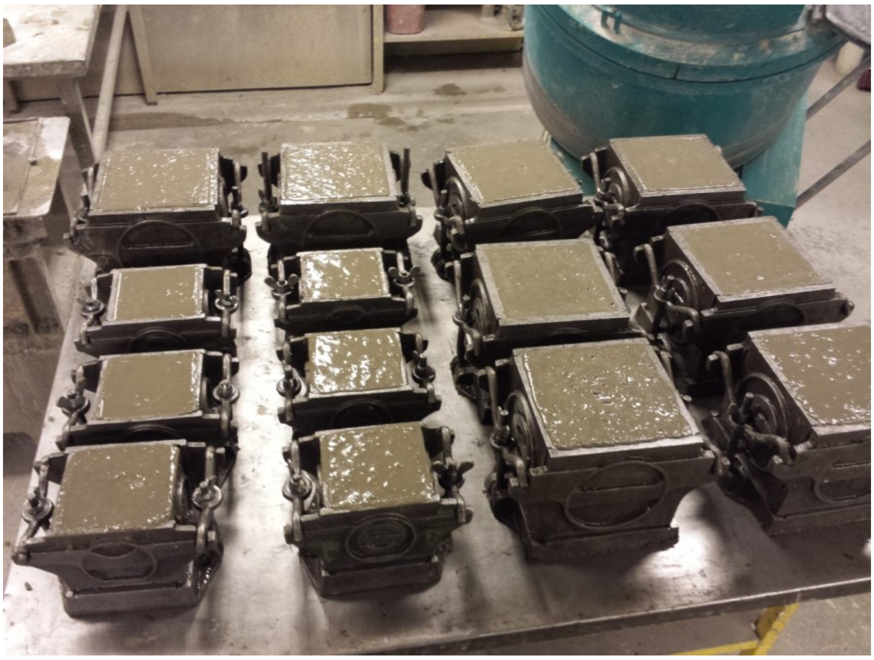
In this chapter the designing and manufacturing of samples used in heating tests, are described in detail. First equipment is introduced. Second the idea of test samples and design of them is explained. Third the making and casting of concrete, all the way from mix design to the curing of samples, is being reviewed. And finally, fourth, the process of cutting samples, drilling penetrating holes to them and installing the plastic pipe with firestop sealing in to the penetration, is discussed.

The purpose of test samples were to act as a part of fire compartments fire barrier wall. Test samples were designed before manufacturing as seen in . Designing depended on the equipment available in concrete laboratory. Also ease of manufacture and heating ovens restrictions for the size of samples were taken into consideration.



Picture 16 Design of test sample

Test samples were casted as cubes with measurements of 150x150x150 mm. With 40 litres of both types of concrete total of 8 + 8 cubes measuring 150 mm and also 6 + 6 cubes measuring 100 mm were casted. These smaller cubes were used for compressive strength tests.



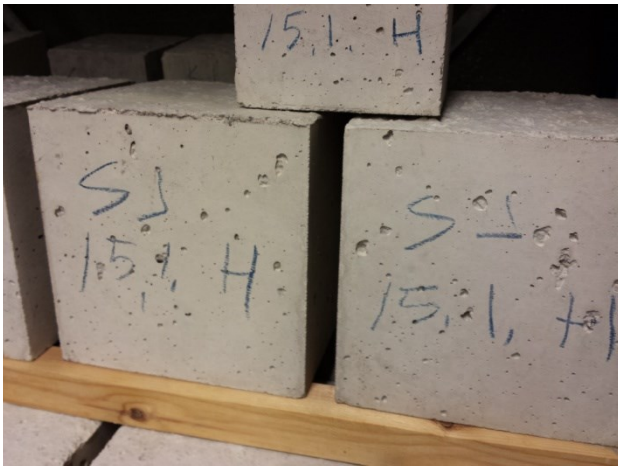
Picture 17 Molds used for casting, including 6 pieces of standard 100 mm cubes and 8 pieces of standard 150 mm cubes

Curing of concrete cubes was done as follows. First after casting molds were covered with plastic sheet (Picture 18) for 24 hours after which samples were demolded. Then both sets of samples were cured in 95% of relative humidity (Picture 19). OPC samples were cured for 7 days, and HPC samples for 5 days, because it wasn't possible to move the samples during weekend. Concrete samples were then transferred to a steady state weather room, in which temperature is constant at 20°C and humidity stays constant at 45 %. Samples were in this room until they reached maturity of 28 days.

Picture 18 Test samples under plastic sheet after casting

During demolding it was clearly visible that the surface of OPC cubes were much smoother than the surface of HPC cubes (Picture 20). One possible reason for this was greater air content of fresh HPC mass. Also compaction was propably done better with OPC, cause fresh HPC was much stiffer and not so easily workable than OPC was. We wanted to avoid segregation and used vibration table only so that the surface of the mold looked smooth. Maybe a little more vibration could have been added to get smoother surfaces for the HPC cubes also.

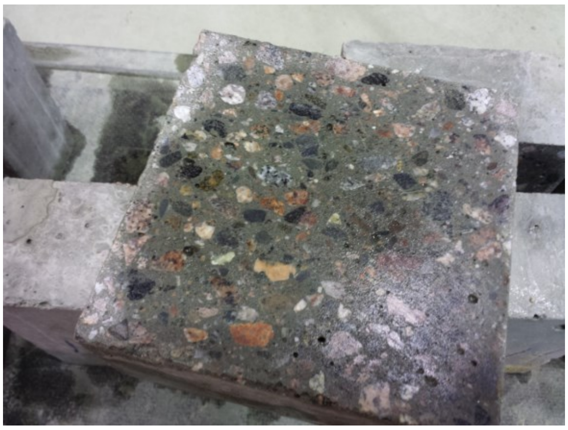
Picture 19 Test samples after demolding in a room with 95 % RH



Picture 20 High strength concrete cubes 23 days after casting

There were no possibilities to use proper fire in testing, nor any proper equipment for testing according to standards SFS-EN 1363-1, SFS-EN 1366-3 and SFS-EN 1366-4. Therefore 8 cubes, with side length of 150 mm, were casted. After proper time of curing, cubes were cut into half with concrete saw. Result was 16 concrete pieces with area of 150 x 150 mm and thickness of 75 mm, see Picture 22 below. Design of these pieces is shown in Picture 16.

Picture 21 Cutting the cubes in half with a concrete saw



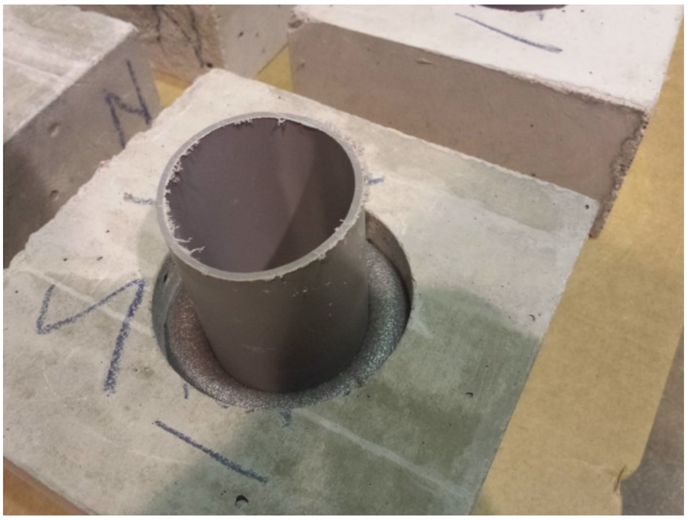
Picture 22 Concrete cube half, still wet after cutting

Holes with diameter of 75 mm were drilled to test samples after cutting each cube into two halves (Picture 23 and Picture 23). Due to excessive amount of water used in cutting and drilling we decided to let the samples to dry out for additional 7 days before finishing the manufacturing process with plastic pipes and firestop sealing. With this long drying period we wanted to prevent the effects of moisture in concrete to adhesion of firestop mastics. Although technical data sheets of products suggested that applying of mastic is possible when the surface of concrete is dry, we wanted to be on the safe side.

Picture 23 Drilling the holes to concrete

Picture 24 Cut and drilled concrete sample

Test samples were finished week after cutting and drilling. For each type of firestop mastic we made 6 samples of concrete and penetrating plastic pipe, made of Polypropylene (PP). Three of these samples were OPC and three were HPC. Mastics were applied as their technical data sheets describe (Nullifire, 2011a; Nullifire; 2011b, Nullifire, 2011c). Sealant mastic SP 525 was also used in sealing according to Illbruck, 2013. We prepared the joints with strand designed to be used in joints before applying mastics (Picture 25). This strand secures the right depth of joint and also provides third adhesion surface for mastic. When sealing the joints, no any special preparation, for example primer, was used when sealing the joints.



Picture 25 Joint strand in place between concrete and pipe

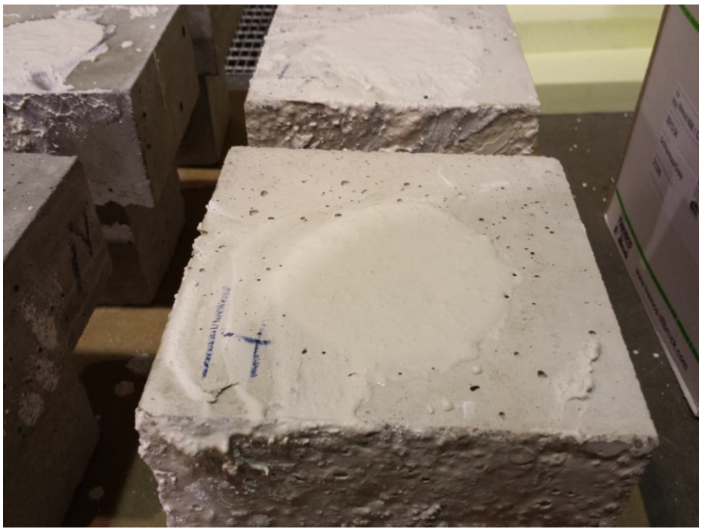
Picture 26 OPC samples with pipes and sealants, from left: acrylic, silicone, graphite and hybrid (non-fireproofed)

Some differences between sealants were already noticed in manufacturing process. Differences noticed were in stiffness and stickiness of the sealants when applying to the joints. FS705 was easiest to apply and felt less sticky compared to others, and in contrast, SP525 was stiffest and stickiest.

After sealing the joints in samples, samples were stored in warehouse for two weeks. This was two times longer than the time required for the slowest drying mastic, FS 705. Conditions in warehouse were slightly different than in steady state storage room where temperature and humidity were fixed to 20°C and 45 %. In warehouse temperature was between 18°C and 22°C and humidity between 30 and 45 %. Detailed schedule of manufacturing process can be found in Appendix C.

Drying period for the gypsum mastic, FR220, was much shorter than for any other, so the FR220 was used to fill in the hole in concrete samples after everything else regarding the samples were ready. When using gypsum mastic to seal the holes we made the mix to water-gypsum-ratio of

1:2 as suggested by technical data sheet (Nullifire 2011d). Mix was easy to pour into concrete samples and didn't need any compaction (Picture 27).



Picture 27 HPC samples holes filled with gypsum mortar

5.6 Testing procedures

In this chapter the tests done to samples before and after heating are described in detail. In some tests different samples were used, as for example in compression strength test. This was due to fact that for some tests specific sized and shaped sample is needed.

5.6.1 Mechanical properties

Compression strength tests were done for cubes manufactured specifically for this. Tests were made for both types of concrete at the age of 28 days. During heating test runs cubes were heated in the oven to study the strength loss after exposure to 200°C. In strength tests we used cubes with a side length of 100 mm and conducted tests according to the SFS-EN 12390-3.

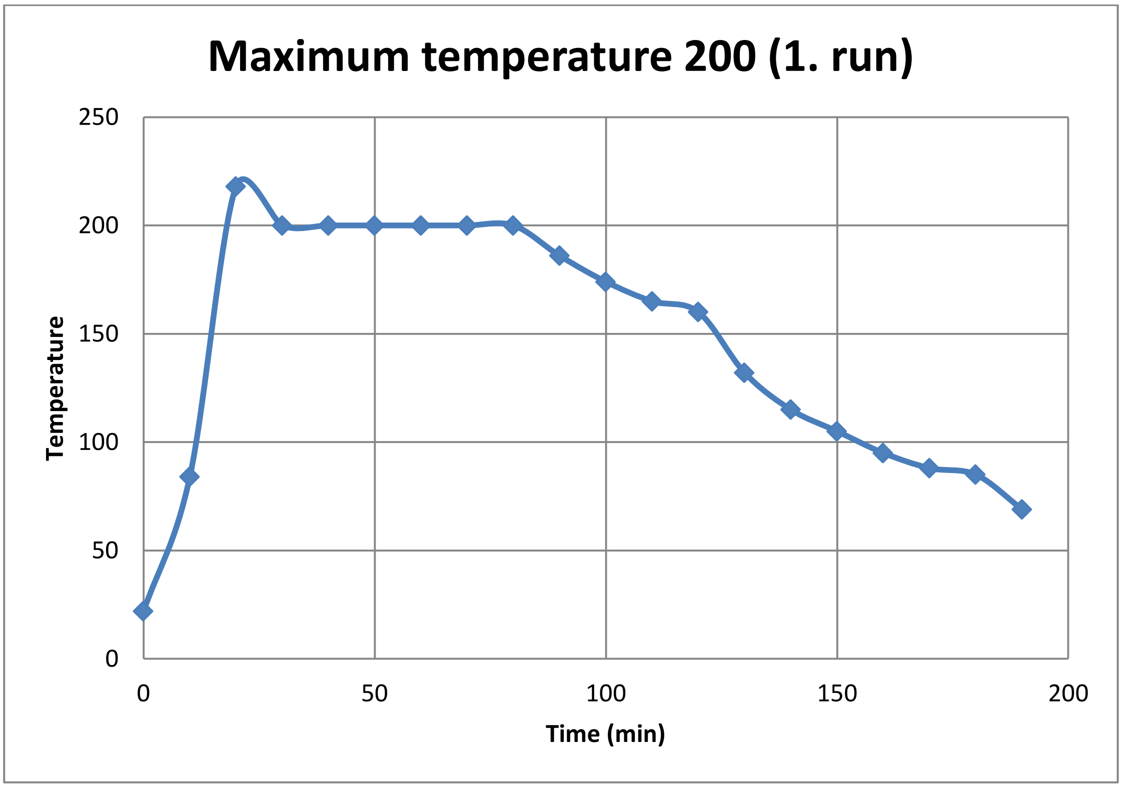
5.6.2 Heating test runs

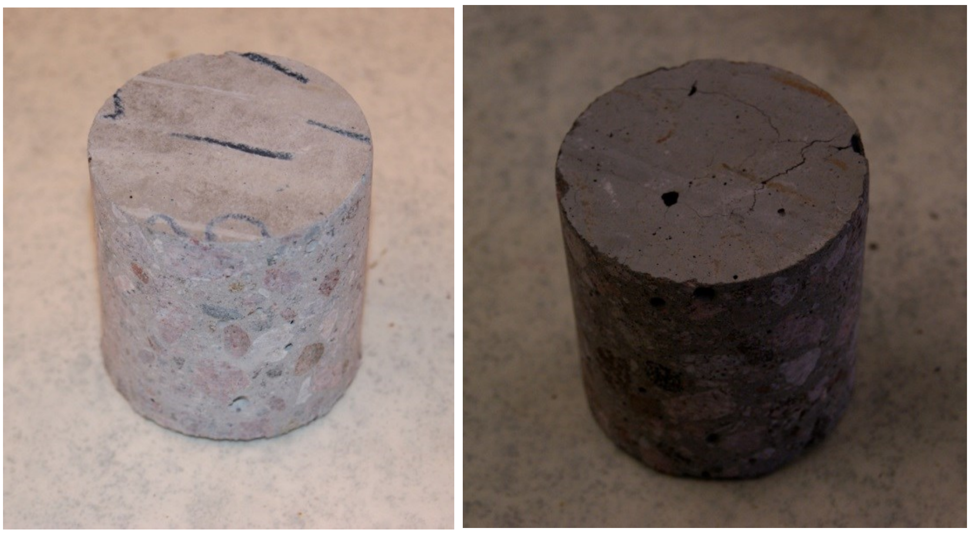
Before heating any samples, some test runs were conducted. Aim was to find out the cooling times of the oven because there were no documentation available for this fact. This was important due to limited time frame during test days. In test runs concrete cylinders got from drilling the holes to samples, were used to evaluate the effects of exposure on the concrete. Oven was programmed to raise the temperature 200°C in 20 minutes.

During the oven was running the programmed heating, the temperatures inside oven were observed and based on these observations graphical presentation of temperature as a function of time was constructed. Notes can be found in Appendix F. Temperatures were observed in 10 minute intervals for most of the heating time. Because of the slow cooling and limited time frame samples were taken out next morning, photographed and studied.

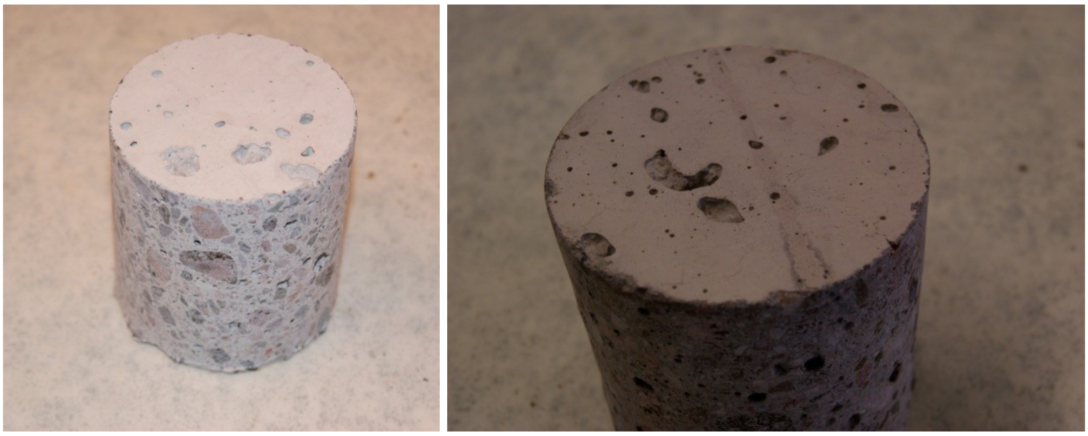
First test run (Table 4) showed that heating to 200°C in 20 minutes raises the maximum temperature in the oven above 200°C. Maximum temperature reached was 218°C. Cooling phase was longer than heating and steady temperature phase combined. Concrete in maximum of 200°C did not crack or show any alteration compared to that before heating. This was somewhat expected result. Results are shown in Picture 28 and Picture 29. After and before photos in this case aren't of the same piece, but of other piece made of same type of concrete.

Table 4 Temperature during test run at 200°C





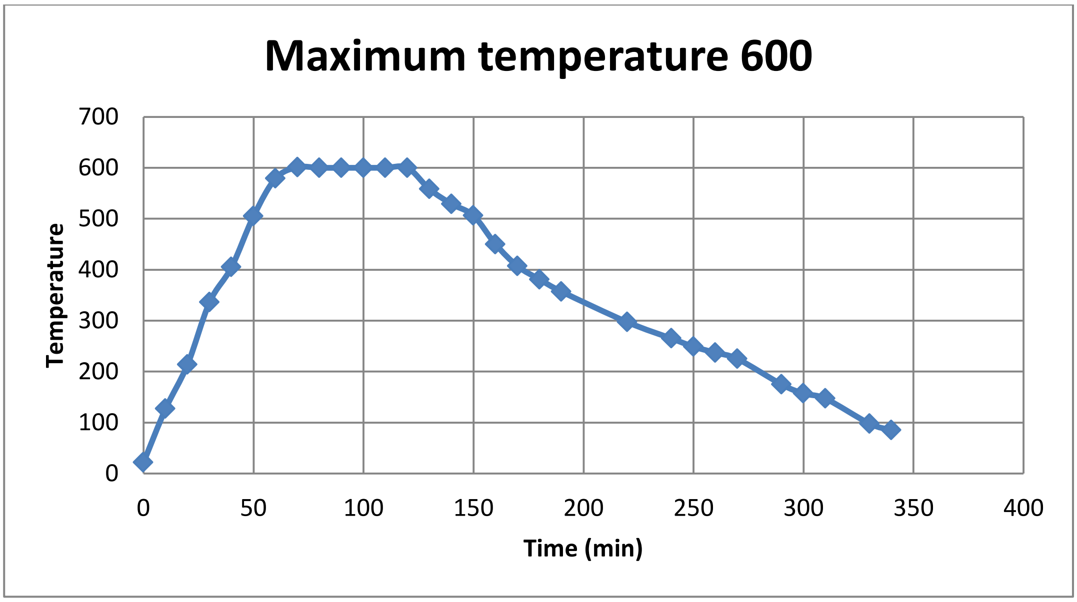
Picture 28 OPC at 200°C



Picture 29 HPC at 200°C

In second test run (Table 5) we programmed the ovens maximum temperature to 600°C, keeping the speed of temperature rise, 200°C in 20 minutes, same as before. However after one hour the temperature inside oven was only 579°C. 600°C was reached after 66 minutes. Concrete in maximum of 600°C was slightly cracked and some aggregates were beginning to deteriorate. HPC pieces were less damaged than OPC pieces, but cracking and deformations in both were not as severe as we expected before. This gave as a reason to do one more test run with even higher temperature, to get closer to real building fire temperatures.

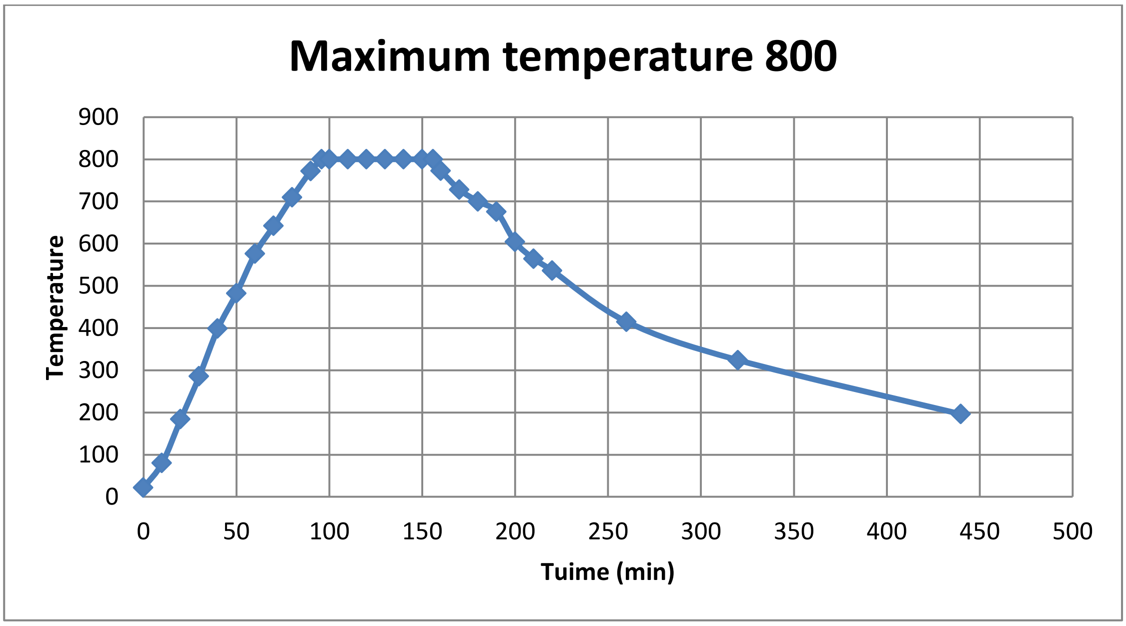
Table 5 Temperature during test run at 600°C



In previous test runs no additional cooling was used. During cooling we observed the dropping of temperature and tried to keep the cooling speed as constant as possible, controlling this with the top hatch and door of the oven. For both runs we tried to keep the cooling speed conservative to prevent any cracking of concrete possibly caused by this.

Third test run (Table 6) was done to try out concretes in maximum temperature of 800°C. Same programming was used for raising the temperature (200°C in 20 minutes, one hour in maximum temperature). Cooling was more rapid at first than in previous test, but slowed down to same grade in lower temperatures. After temperature dropped to 500°C, we used hatch and door in the same way as in previous test trying to achieve same temperature changes. We used pieces stored in two different kinds of condition. Others were kept at 20°C and 45 % of relative humidity and others first in same condition and later in temperatures between 18°C and 22°C and relative humidity between 30 and 45 %. Previously mentioned is also identical to all test samples used in next chapter.

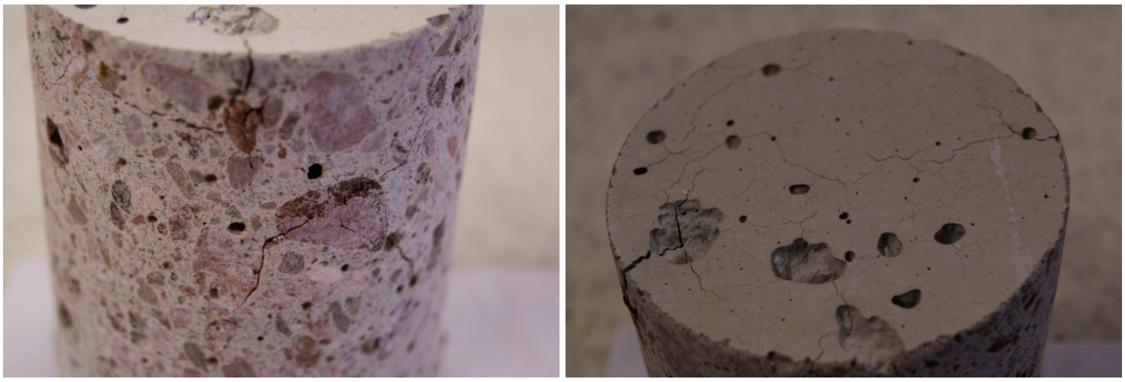
Table 6 Temperature during test run at 800°C



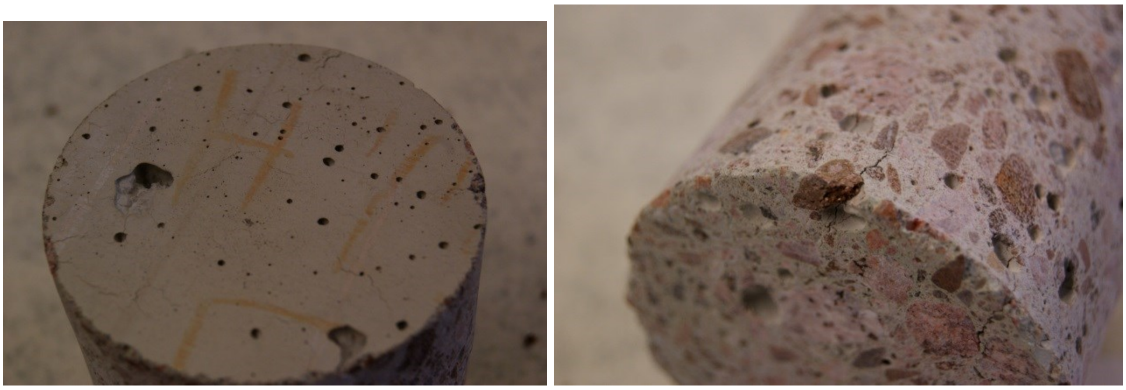
Picture 30 OPC 45 % at 800°C

Picture 31 OPC 30 % at 800°C

Concrete in maximum of 800°C was cracked and showed clear signs of aggregates deterioration as well as concretes. Also some spalling happened to the OPC pieces. HPC pieces again were less damaged and smaller cracks were visible. Probably the reason behind this is the smaller water-cement ratio of HPC samples, so there is less water to vapour from inside the concrete.



Picture 32 HPC 45 % at 800°C



Picture 33 HPC 30 % at 800°C

5.6.3 Heating tests

Heating of the samples was done during one week, on four consecutive days. Size of the oven was a restrictive factor, because only five samples fit inside the oven at the same time. Also only one test per day was possible due to slow cooling of the oven. This meant that we needed two days to heat OPC and HPC samples in two temperatures. More detailed schedule can be found in Appendices.

Samples were for 1 hour in both temperatures, after which oven was left to cool down. Because of this cooling down phase, and also the warming up phase, the samples were exposed to high temperatures longer than just one hour. Graphs of ovens temperature can be found in Table 7 and Table 8 below.

Table 7 Temperature during testing at 200°C

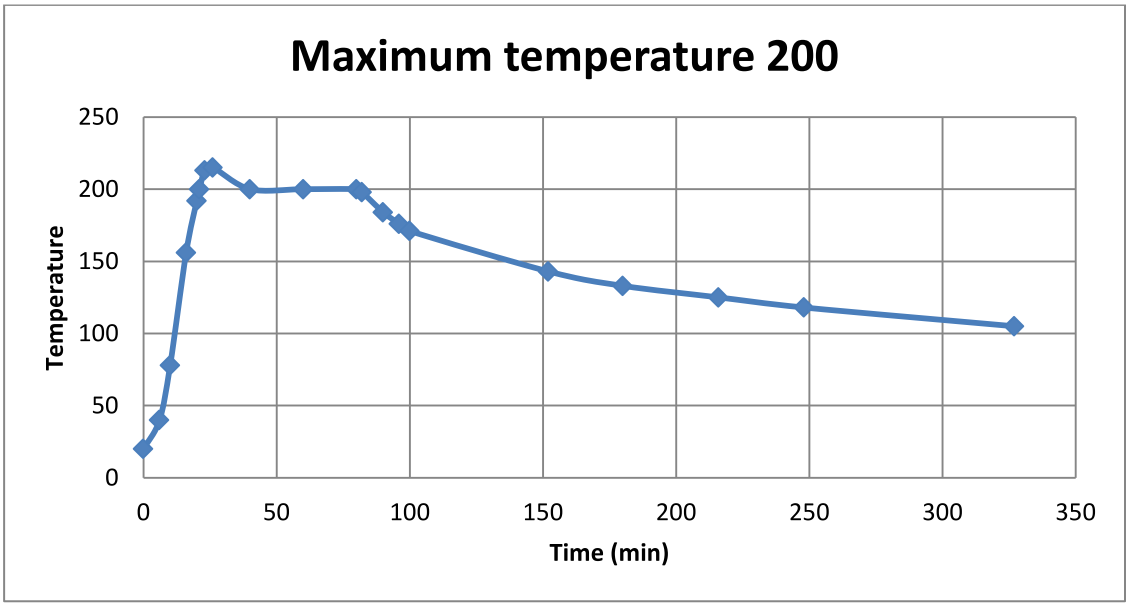
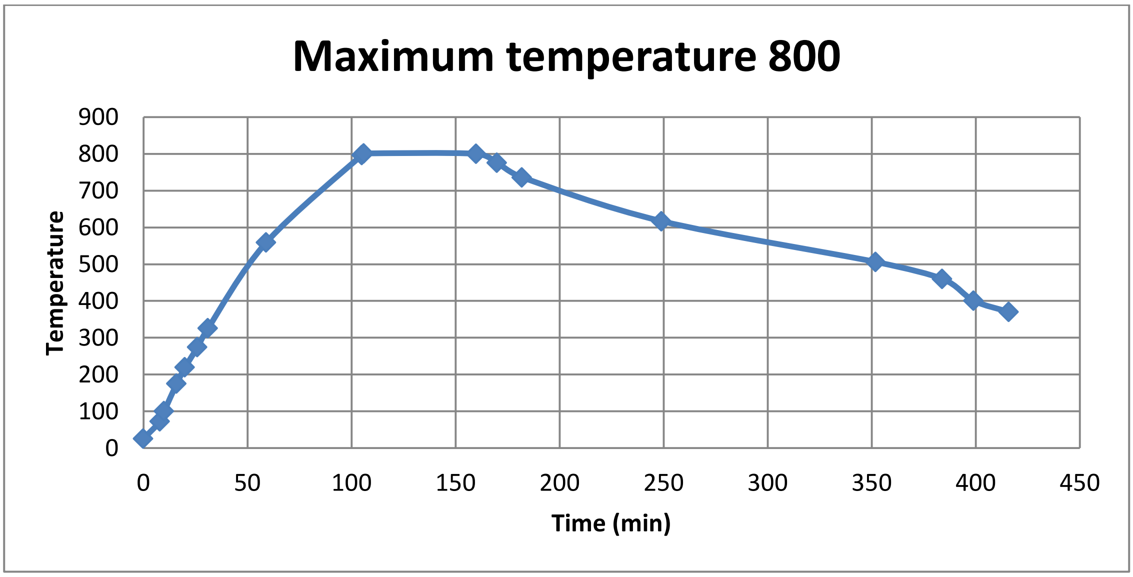


Table 8 Temperature during testing at 800°C



Each test sample was placed in the heating oven, so that pipe was horizontally and concrete piece acted as a wall, which was penetrated by pipe. Samples were heated to temperatures of 200°C and 800°C. Heating and cooling phases followed the patterns achieved from test runs in Chapter 5.6.2. Despite, observation of temperature was done during tests, but in random intervals. After heating period, samples were photographed and examined as described in chapter 5.6.

5.6.4 Visual inspection

Visual inspection was performed to the samples before heating and after heating. When comparing the samples after heating, they were compared to reference samples, and photos taken before heating. Not every sample was photographed before and after heating, because the structure of concrete, in samples inside same category of concrete type, is same regarding of what firestop mastic were used. Visual inspection concentrated mainly on studying the cracking patterns and deformations of samples. Adhesion between the concrete and mastics was also observed.

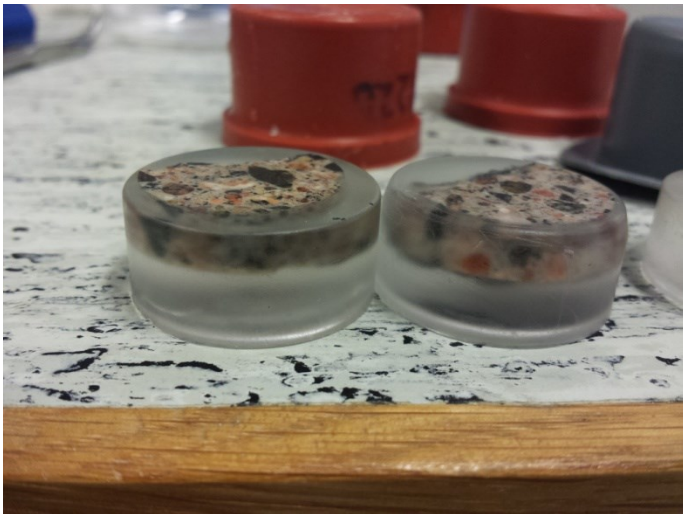
5.6.5 SEM analysis

Contact surface between concrete and mastics was examined with Scanning Electron Microscopy (SEM). Before examination, samples needed some preparation, which is explained in two different parts. First preparation was to take small sample of concrete, which was in contact with fire mastics and exposed to high temperatures. This was done only to samples which were in 200°C. Concrete in 800°C was mainly too brittle to endure the sample taking process.

Picture 34 Removing remains of pipe and mastic.

Picture 35 Samples were taken from the surface of penetration.

First, the remaining mastic and pipe was removed (Picture 34). Second, samples were drilled of the concrete (Picture 35) and then cut in to pieces about 2,5 cm in diameter and 0,5 cm in thickness. Samples were taken from both OPC and HPC samples, which had silicone and intumescent sealants and gypsum mortar. This decision was based on differences in behavior between these combinations observed after heating test. Samples were then impregnated with epoxy resin and polished after hardening. Samples were analysed with SEM and pictures were taken.



Picture 36 Impregnated HPC samples.

5.6.6 Weight loss during heating

Each sample was weighted and marked before putting in the oven. After heating and cooling each sample was weighted again to find out the weight loss caused by heating. This weight loss consists of concretes weight loss, plastic pipes weight loss and the weight loss of firestop mastic. This was done to see if there is some significant alterations between certain concrete and mastic combinations or are the changes somewhat same in every sample. Samples were weighted in 20°C, after cooling down the oven overnight.

5.7 Test results and their analysis

Results from tests are reviewed in this chapter. Visual inspection is discussed in four parts. First two parts discuss OPC and HPC samples in 200°C, because results are similar regarding firestop mastics. Also behaviour of different concretes is similar in this temperature. Next two parts discuss OPC and HPC samples in 800°C. Results from ESM are discussed next and finally weight losses are evaluated and addressed.

5.7.1 Mechanical properties

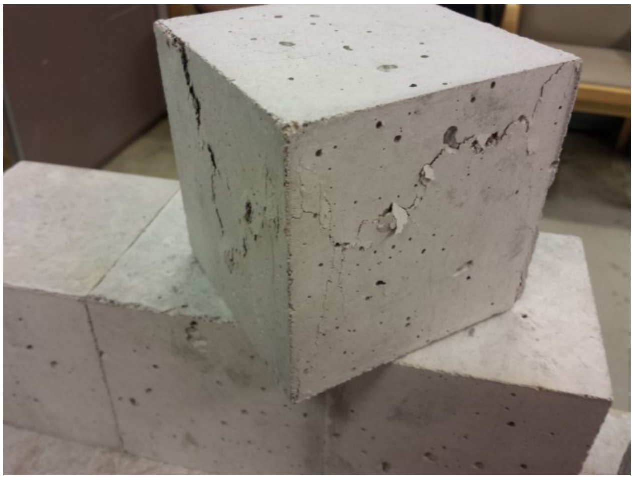
Results of compression strength tests at the age of 28 days and after exposure to 200°C are shown below in Table 9 and Table 10. Cubes were put in the oven at the age of 72 and 74 days, and tested for compression strength after heating at the age of 92 and 94 days. More detail about compression strength tests can be found in Appendices D, E, G and H. Picture 37 shows HPC test sample number 1 after compression strength test.

Table 9 Compression strengt at the age of 28 days

	OPC			HPC		
Test sample number	1	2	3	1	2	3
compression strength [N/mm2]	38.32	39.59	38.64	96.1	100.5	94.3
compression strength, mean values [N/mm2]		38.85			97	

Table 10 Compression strength after exposure to 200

Test sample number	OPC 1	2	3	HPC 1	2	3
compression strength [N/mm2]	42.83	42.61	43.76	108	106.4	98
compression strength, mean values [N/mm2]	43.07			104.1		



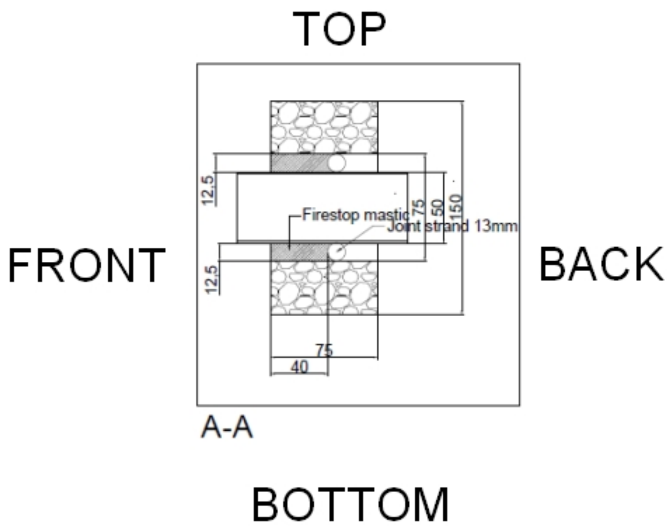
Picture 37 Crack formation on HPC test sample during compression strength test

Heating to 200°C in 20 minutes, and 1 hour exposure time, did not effect the compression strength of tested samples. Both types of concrete had gained more strength comparing to test at the age of 28 days. Samples had age difference of about 60 days. Hence it was not possible to determine did the exposure to 200°C have any effect at all. Furthermore it was clear that neither OPC nor HPC suffered strength loss which would cause problems to their designed performance.

5.7.2 Visual inspection

The results are reviewed and compared to each other and also to pictures taken before heating.

Picture 38 shows the naming of surfaces in discussion.



Picture 38 Surfaces of test samples

5.7.2.1 Adhesion

Adhesion was observed during drilling sample pieces for SEM. FR220, FS703 and FS705 were the mastics with best adhesion and were most difficult to remove. FR220 did not show any loss of adhesion. FS701 had less adhesion than previously mentioned mastics. Even though mastic (FS701, FS705) had lost adhesion on upper part of the penetration, it did not remove easily. FS701 and FS705 kept the form of penetration after removing. However FS705 left stains on the contact surface in contrast to FS701 which left virtually no signs on contact surface. Also FS703 left stains to concrete. SP525 was brittle and mostly crumbled off from concrete. Mastic was soft and in some parts sticky.

5.7.2.2 OPC in 200°C

As expected from heating test runs, concrete did not look damaged at all. There were no visible cracking or color changes in concrete in any one of the samples. In every sample the plastic pipe was melted to various degrees.

Acrylic mastic, FS701, lost some of its adhesion with the concrete on the upper side of penetration. Adhesion between pipe and mastic was also lost, and pipe was collapsed to the bottom of penetration. This means air tightness loss and possibility for exhaust gases to move through the penetration, which is definitely not desired outcome for this low temperature. Of course, acrylic mastics aren’t supposed to be used with penetrations consisting lots of movement or deformations, so this observation is not so important in this case. However acrylic mastic should expand little and increase its volume. Based on he obtained result it’s hard to tell if there has been any expanding or not.

Picture 39 FS701 OPC sample after test at 200°C

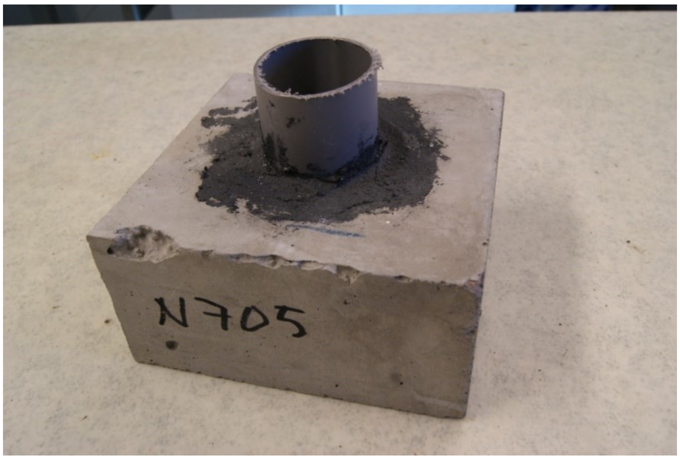
Silicone mastic, FS703, performed best in this lower temperature test. No adhesion to concrete was lost and therefore air tightness between concrete and melting pipe wasn’t lost either. Mastic was intact and felt elastic like before test.

Picture 40 FS703 OPC sample

Picture 41 FS703 OPC sample after test at 200°C

Intumescent mastic, FS705 is classified as EI120, if used as described in its technical data sheet. According Nullifire (2011c) it is supposed to be activated in temperatures between 250°C and 300°C. Therefore, it was not surprise that there were no signs of expansion or charring in test. However, Deformation of melting pipe broke the seal between mastic and pipe, causing crack visible to human eye. 200°C temperature is possible in case of compartment fire, when there are limiting factors to the growth of fire. Hence, adhesion lost already in low temperatures cannot be in any case considered as a desired outcome.

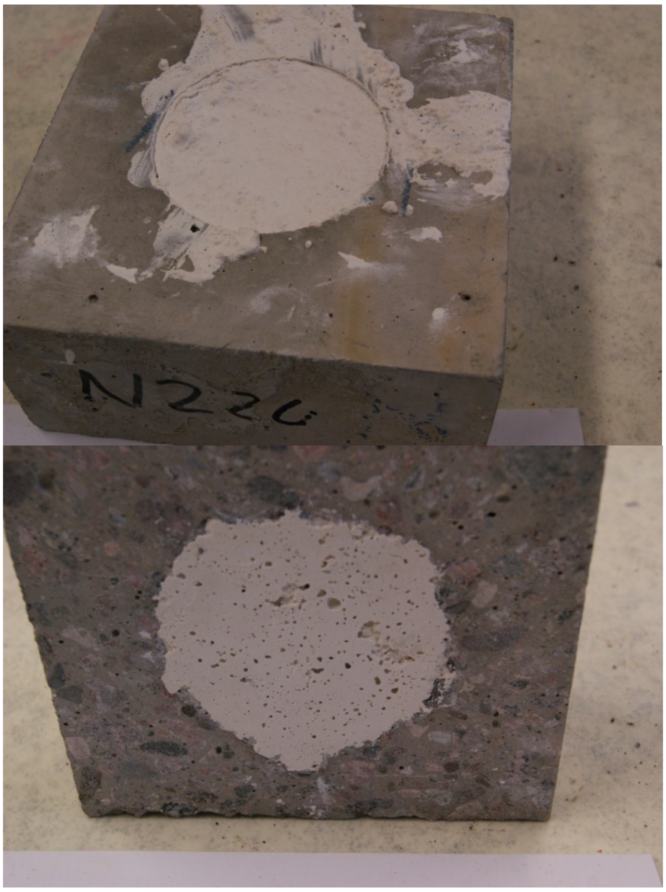
Of course the exposure time to high temperatures in our test exceeds those, which are given for the mastic based on proper fire tests. Test samples were nearly 150 minutes in temperature over 150°C. Judging by this test, intumescent mastic does not perform best in this kind of situation. It performed nearly identical to acrylic FS701.



Picture 42 FS705 OPC sample

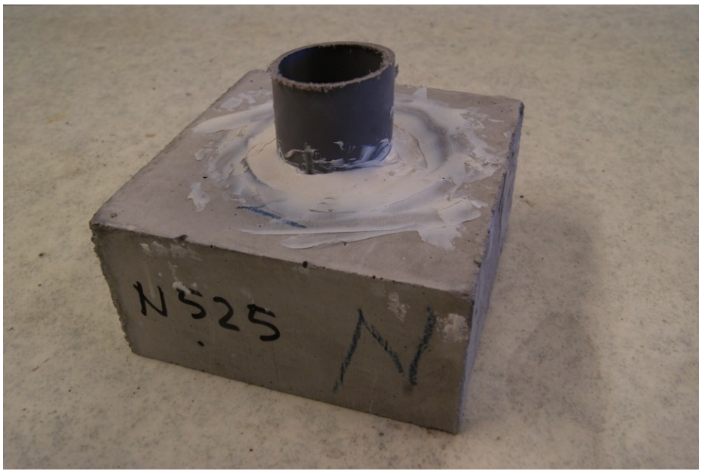
Picture 43 FS705 OPC sample after test at 200°C

Gypsum mortar, FR220, did not show any signs of damage. If it would have been used similar to other mastics, in a penetration with pipe, the contact surface between concrete and FR220 would have been most likely still intact and secure. Difference would have been witnessed in the contact surface of pipe and gypsum.

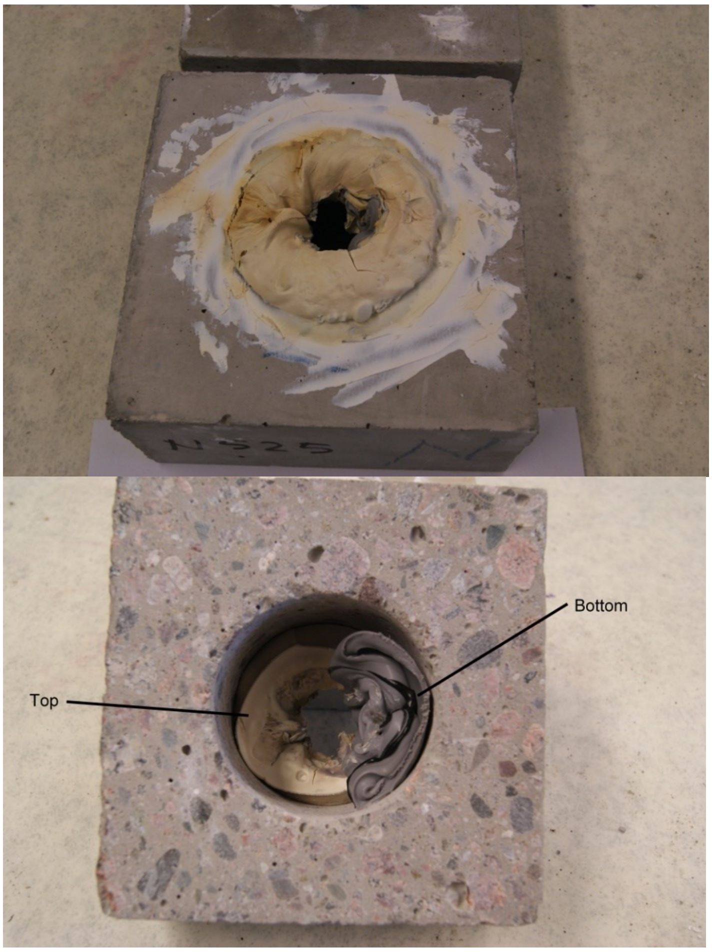


Picture 44 FR220 OPC sample after test at 200°C

Normal operating temperature for SP525 is up to 40°C and short term durability temperature is up to 90°C. It has no fireproof properties and it was revealed clearly in heating tests. SP525 was the only one of the mastics in this temperature, which expanded and increased its volume. However the pipe was melted to the bottom of penetration as seen on Picture 46 Also it was the only one which changed in color, as can be seen in Picture 45 and Picture 46. When removing SP525 and plastic pipe, the mastic was sticky and soft, unlike other mastics after heating.



Picture 45 SP525 OPC sample

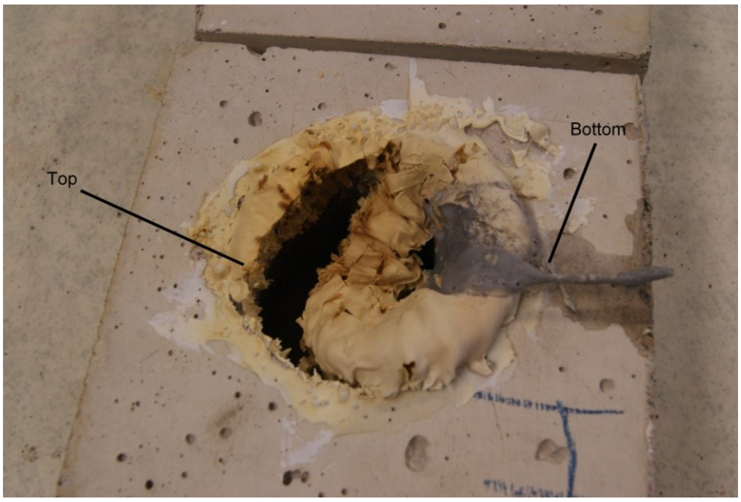


Picture 46 SP525 OPC sample after test at 200°C

5.7.2.3 HPC in 200°C

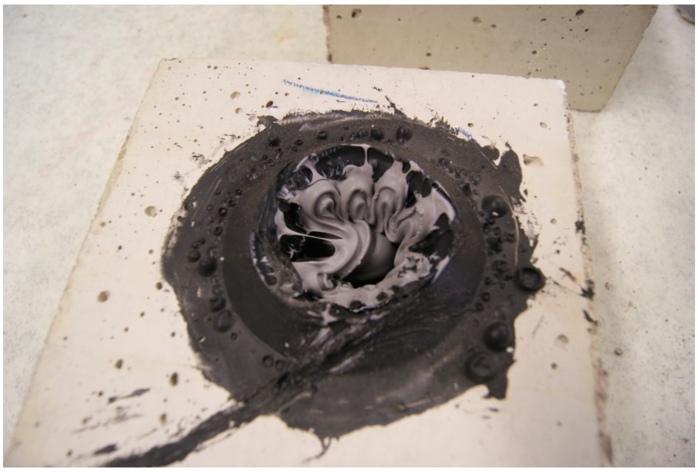
Results of heating HPC samples in 200°C were identical or nearly identical to those mentioned earlier regarding OPC samples.

SP525 showed most difference in this case, because it lost totally it's adhesion to concrete on the upper side of penetration. Possible reason for this could be poorer finish of sealing or difference in the thickness of seal. Nevertheless, these are reasons depending on the user of mastic, not mastic itself and cannot be discussed more on this case.



Picture 47 SP525 HPC sample after test at 200°C

Other difference was observed in FS703, in which forming of air bubbles inside mastic was visible. Propable cause was water vapour from concrete, but it is uncertain why same did not happen in the case of OPC sample.



Picture 48 FS703 HPC sample after test at 200°C

5.7.2.4 OPC in 800°C

There were some notable differences in how severe the concrete was damaged on different samples. And of course there were notable differences in comparison between samples which were exposed to 200°C.

When taking FS701 samples out of the oven, the mastic was still intact and surrounded the penetration nicely. But when placed on table and prepared for photographing, the mastic crumbled to pieces as seen on Picture 49. Concrete was cracked in many places and spalling was also visible in the corner. Cracks were largest on the outside surfaces of sample, and inside penetration cracks were smaller. Mastic did not seem to have any adhesion to the concrete inside the penetration, but the small layer on the front of sample, was still attached to concrete. This, however, does not serve any function to performance of firestop in this case.

Picture 49 FS701 OPC sample after test at 800°C

FS703 had lost some of its form and silicone mastic had turned porous both on the surface and inside. Colour had turned from black into grey, and mastic was brittle like in the case of FS701. Cracking was more evenly distributed around the concrete in this sample than in case of FS701. Also there were more cracks.

Picture 50 FS703 OPC sample after test at 800°C

FS705 Intumescent mastic had totally lost its form and firmness. It had turned into char, piling up into two piles on the both sides of the sample in the oven. Amount of char is clearly visible in Picture 58, which was taken after test at 800°C of HPC samples, but same char formations applied also in this case. Concrete was in better condition than in any other sample at 800°C.

Picture 51 FS705 OPC sample after test at 800°C

SP525 looked quite different than rest of the mastics. It did not seem as intact as for example FS703, even though it was still holding its form. It had expanded and looked porous inside. Concrete had also cracked a lot and spalling had occurred in corner of sample. Mastic did not have any adhesion inside penetration. Only the thin surface on the front surface of concrete seemed to have some adhesion.

Picture 52 SP525 OPC sample after test at 800°C

Sample with FR220 seemed to be most damaged. There were couple of possible reasons for this. First one was the different design of the sample. Because in this sample the whole penetration was filled with gypsum, there was less surface of concrete visible and therefore the vaporization of water happens through smaller surface area than in other samples. Second reason could have been the properties of gypsum compared to properties of other mastics. Because gypsum contains water in its structure like concrete, there is more of vaporizing water in test sample than in other samples. Part of water from gypsum vapours to the contact surface of concrete inside the penetration and causes more stress on this area. This is not happening with the other mastics, cause they do not have water to vaporize and only part of the surface in penetration is covered by mastic.

In this case the gypsum piece could be removed from the penetration. Picture 54 shows the cracking formation on the gypsum. This is very minor cracking in comparison with concrete.

Picture 53 FR220 OPC sample after test at 800°C

Picture 54 Removed FR220 piece

5.7.2.5 HPC in 800°C

At first look every HPC sample seemed to be in pretty decent condition compared to OPC samples in previous chapter. This was mostly caused by differences in water/binder –ratios, which meant less evapourable water in the case of the HPC samples. In this case explosive spalling was predicted to be more likely than in the case of OPC samples. However, this proved to be a wrong prediction. Due to slow rising of temperature, the tensions inside concrete structure did not become strong enough to cause spalling. Also previously mentioned low amount of evapourable water had preventive effect on spalling. Color of the concrete changed a little, as some darkening was visible on some surfaces.

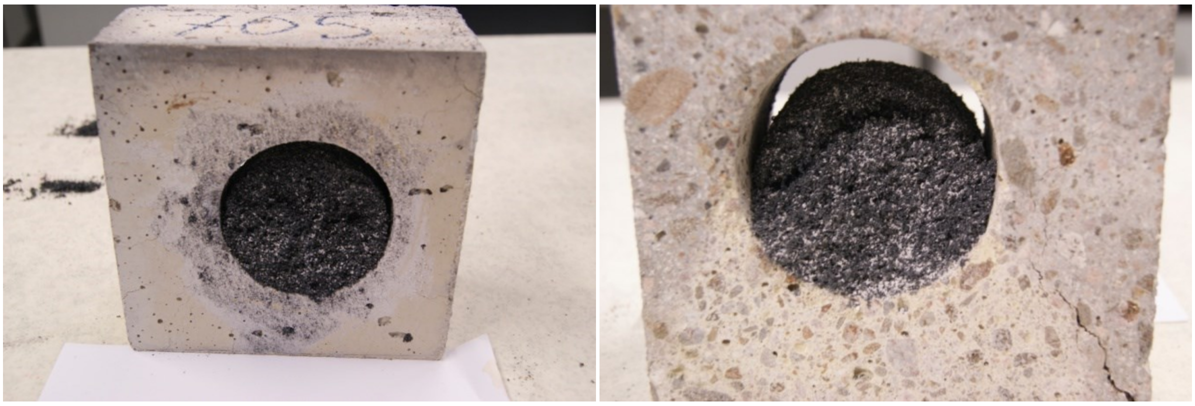
FS701 performed very close to the OPC sample. Concrete performed noticably better than the OPC, which had cracked severily. This time it was possible to take a photograph before the mastic collapsed and crumbled.

Picture 55 FS701 HPC sample after test at 800°C

In the case of HPC, FS703 had totally collapsed on to the bottom of penetration, barely retaining its form. Concrete had few visible cracks and was colored slightly more grey. Signs of bubble formation on the surface of mastic was visible, as in lower temperature test for HPC sample. Appeared that this could have something to do with the concrete type, because same effect was not visible in the case of OPC samples.

Picture 56 FS703 HPC sample after test at 800°C

FS705 was again totally charred and did not resemble a proper firestop in any way. No stains or signs of mastic were left on the concrete in the penetration. Concrete, however, seemed intact disregarding one large crack in the corner of the sample.



Picture 57 FS705 HPC sample after test at 800°C

Volume of FS705 had increased extensively, as shown in the charring formation in Picture 58. The char was lightweight and did not have any of the mastics properties prior to the heating.

Picture 58 Charring of FS705 HPC sample after test at 800°C

HPC sample with FR220 seemed again most damaged comparing to other HPC samples. mastic was intact and again only minor cracking was visible. Concrete was cracked most in comparison with other HPC samples. Picture 59 shows how the whole top part of sample is cracked through. It was clear in this case that if penetration inside concrete was filled entirely with gypsum mortar, it effected negatively on the endurance of the concrete. This was same observation as in the case of OPC samples.

Picture 59 FR220 HPC sample after test at 800°C

Picture 60 Back side of FR220 HPC sample

SP525 had expanded and still had some adhesion left. This is again different observation compared to all the other cases involving SP525. This indicates that no prediciton can be made about behavior of non-fireproofed, in this case M1-classified, sealant mastic at high temperatures.

Picture 61 SP525 HPC sample after test at 800°C

5.7.3 SEM analysis

SEM analysis was performed to reveal possible alterations in the structure of the concrete due to firestop sealant mastics. Six samples from three different mastics and two different concretes were prepared. Sample pieces were taken from test samples used in the heating test at 200°C, because at higher temperature mastics and concrete were too demolished for proper taking of samples for the SEM. Tests samples are described in Table 11 below.

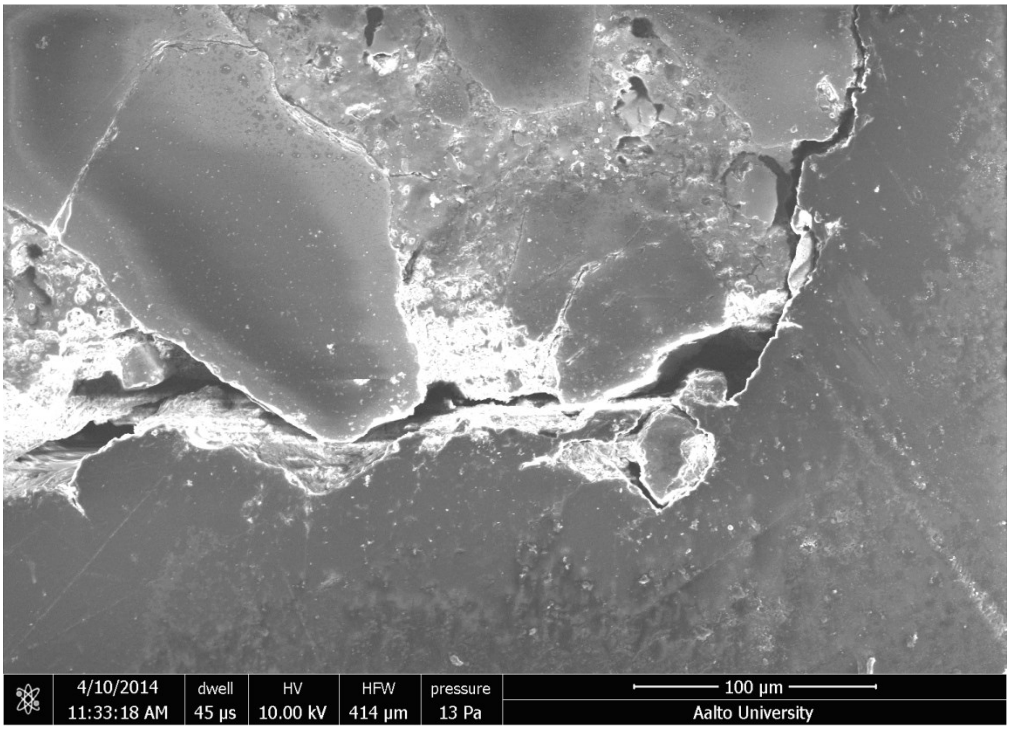
Table 11 Test samples used in SEM

Sealant mastic \ Concrete	OPC	HPC
FS703	N3	H3
FS705	N5	H5
FR220	N2	H2

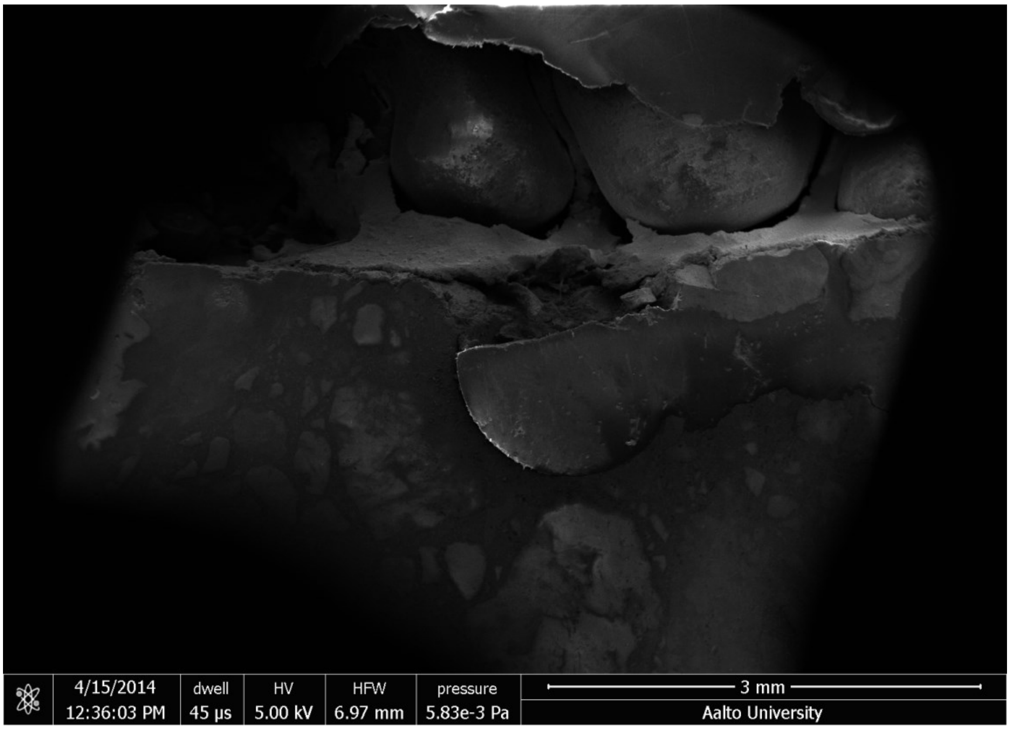
Mastics FS703 and FS705 were choosed for the SEM, because they behaved differently in heating tests. Adhesion loss was witnessed in the case of FS705, opposite to good adhesion in the case of FS703. FR220 was included, because of the different properties compared to two previously mentioned. FR220 is totally non-elastic and performed best in the heating tests including tests at 800°C. In contrast, FS703 is the most elastic mastic used in tests and performed similar to other mastics at 800°C.

Aim of the SEM examination was to determine whether the mastics had penetrated the structure of concrete, and possibly fill some micro cracking inside the concrete, or did they just interact with the surface. Manufacturing process of the samples for the SEM had probably affected the samples of FR220 by dissolving remaining gypsum, because lots of alcohol were used.

In general SEM did not provide any result suggesting that any of the three mastic had penetrated inside the concrete. Cracking formations in the concrete were not abnormal and there were no signs of mastic residues in the cracks.

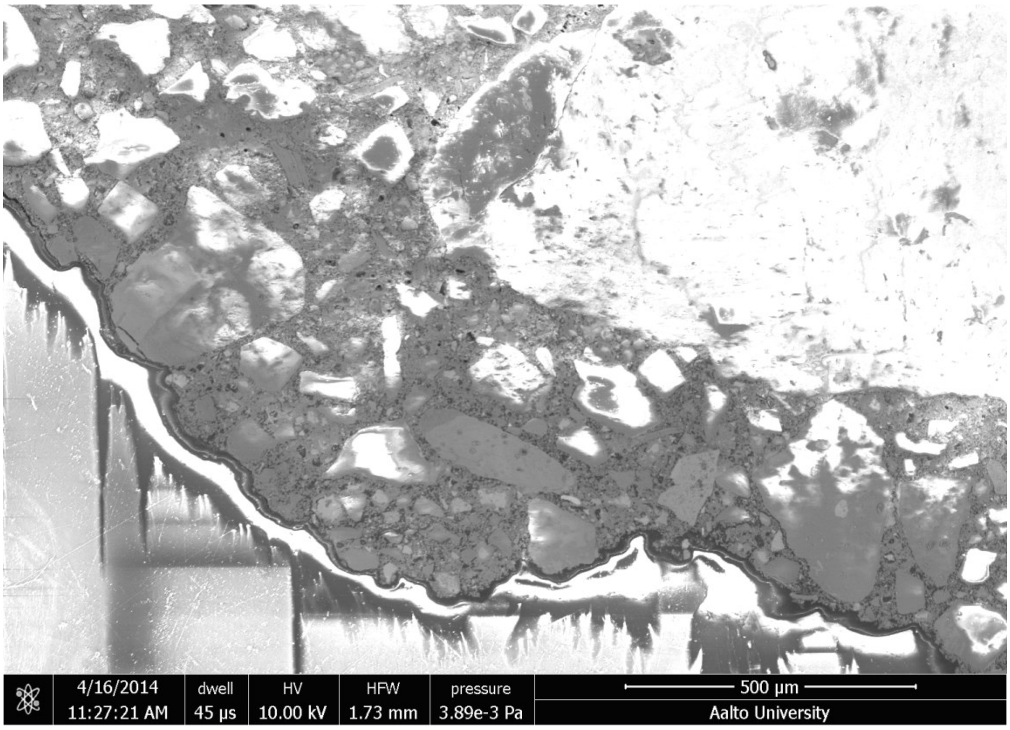


Picture 62 sample N3

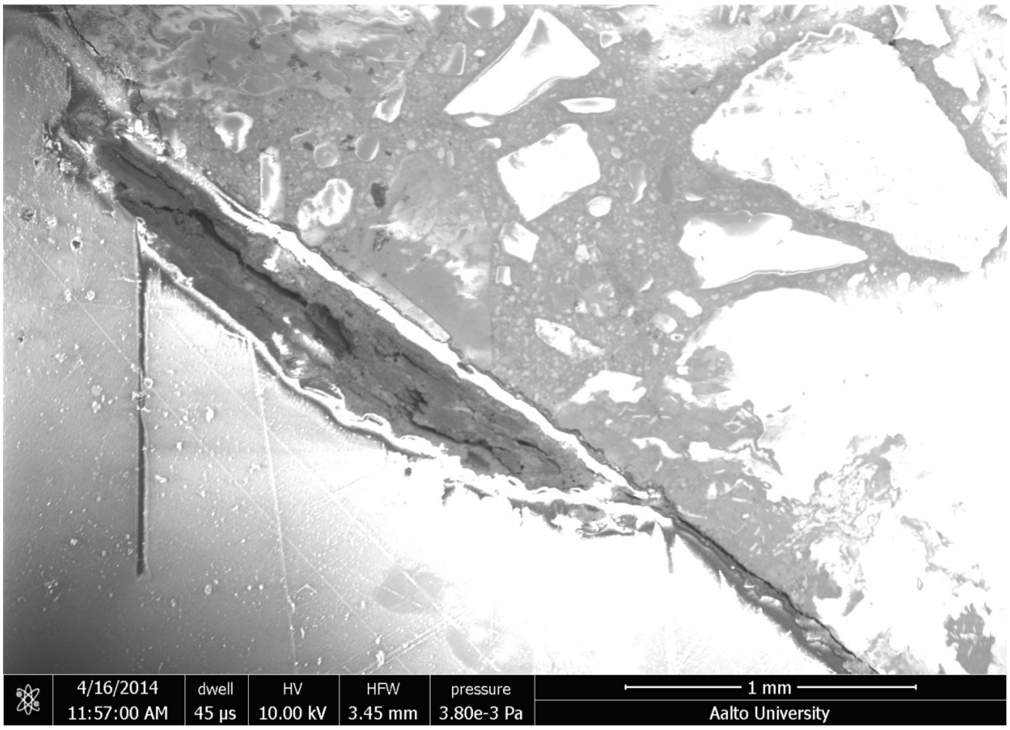


Picture 63 sample H3

When removing FS705 mastic from the concrete, it left clear layer of stains on the concrete. This can be seen in Picture 64 and Picture 65 below. There were no visibly cracking inside the concrete on either one of FS705 samples.

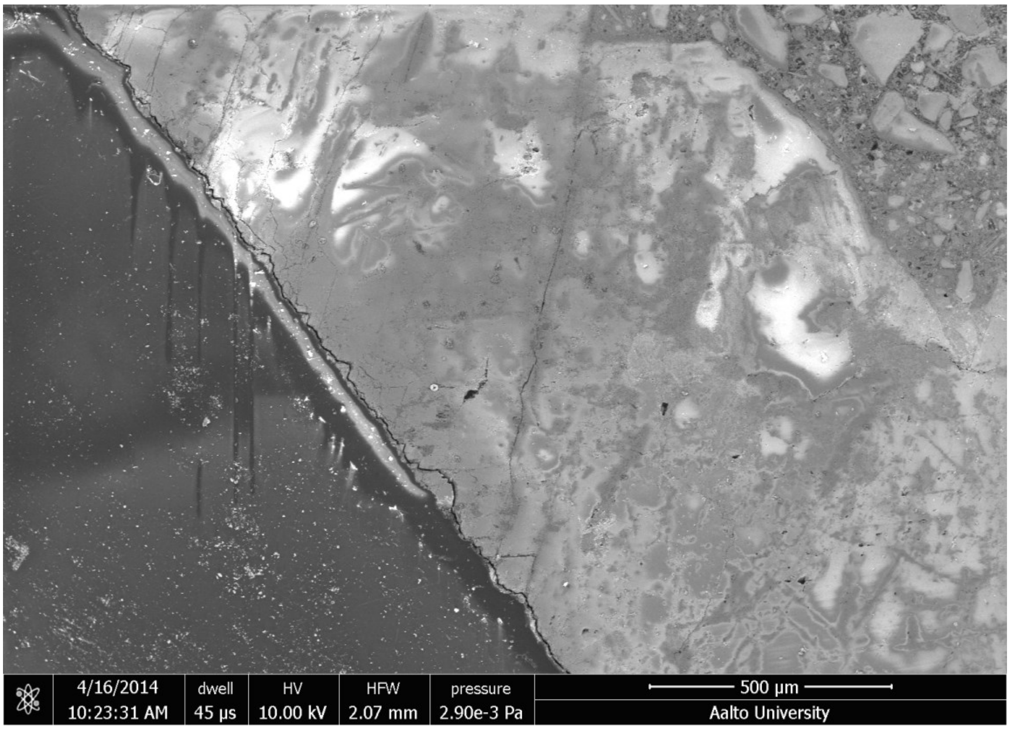


Picture 64 sample N5

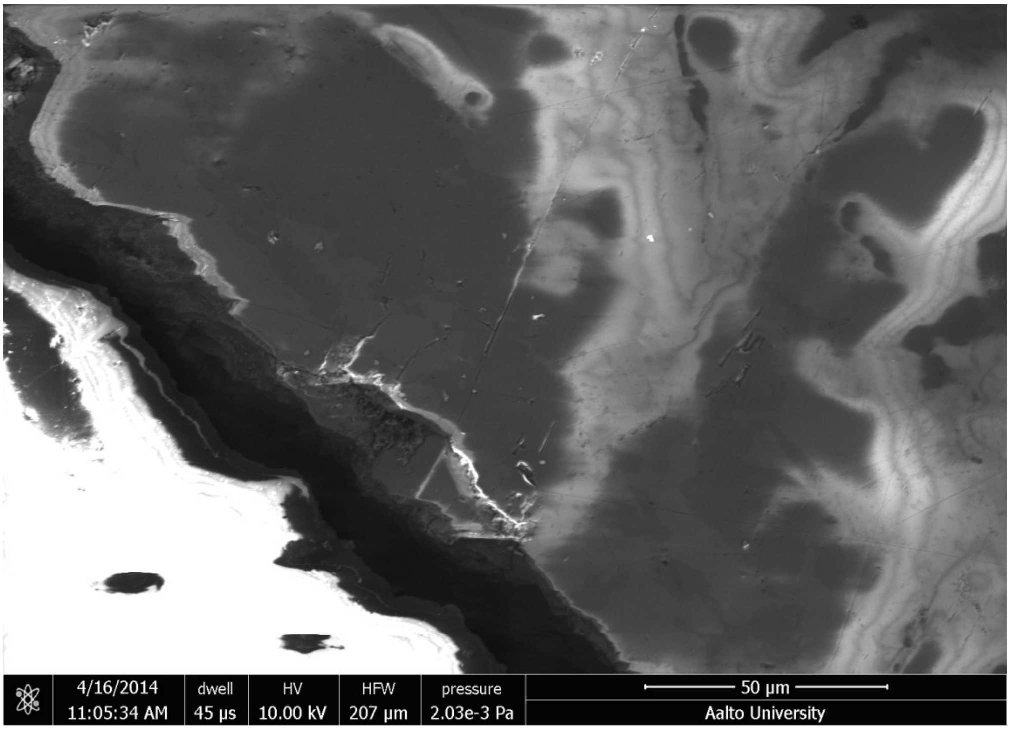


Picture 65 sample H5

Samples N2 and H2, which were taken from FR220 test samples, showed most cracking inside the concrete. This result is consistent to visual inspection of FR220 samples. At 800°C concrete in FR220 test samples were most damaged. Hence it would be expected that concrete in lower temperature also showed signs of damage.



Picture 66 sample N2



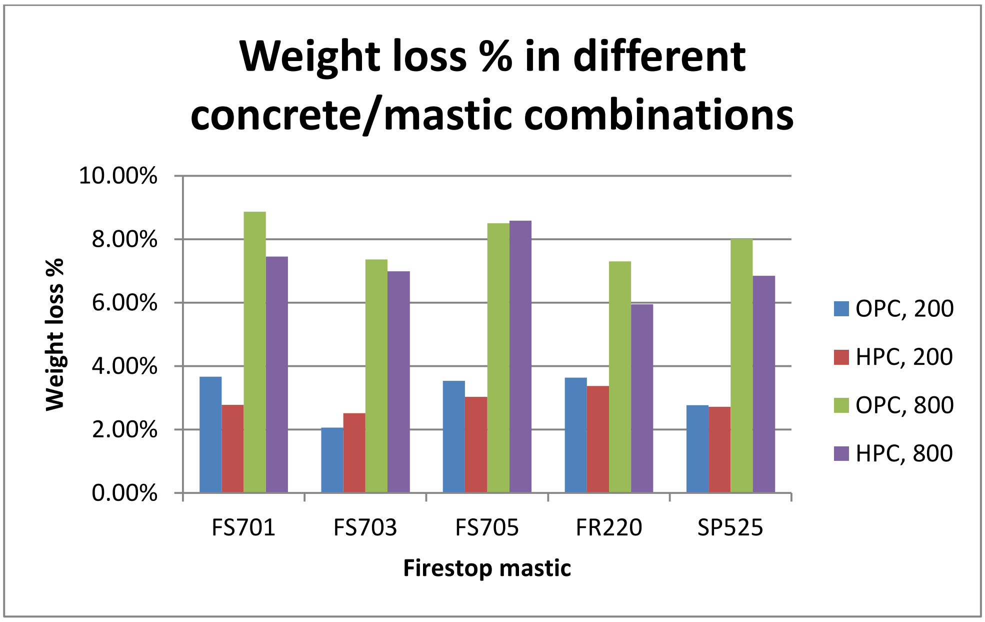
Picture 67 sample H2

5.7.4 Weight loss

Table 12 shows the percentage of test samples weight lost during heating. Weight losses in lower temperature at 200°C were around 3% and in 800°C varying between 6% and 9%. In both temperatures the OPC samples lost more of their weight than HPC samples. Exceptions were FS703 at 200°C and FS705 at 800°C. At 800°C spalling of concrete was greater in some samples and not every piece of spalled concrete was possible to weigth with corresponding sample. This lead to inaccurate results concerning samples at 800°C, which can be responsible for the difference in the case of FS705 OPC and HPC samples weigth loss. In the case of FS703 OPC and HPC samples at 200°C the explanation for different behavior comparing to trend amongst others can not be stated. Judging from the Picture 41 and Picture 48 there were no significant difference than the formation of air bubbles inside FS703 HPC sample. In both cases pipes were melted inside the penetration and concrete showed no signs of damage.

Altogether, FS703 and FS705 samples had more similar results in weight loss between two different concretes. Otherwise there were greater difference in weigth loss between OPC and HPC samples, and almost in every case OPC sample lost more weigth than HPC sample.

Table 12 Weight loss of test samples during heating



6 Conclusions

Two case studies introduced differences in approaches towards fire safety. Cases were different in the design and implementation of firestops. Even though, in the first case results could have been much more severe due to lack of proper firestops, there were no casualties. In the second case failure and danger was caused mainly by improper usage of fire doors and other fire safety measures, for example fire detectors. However, the importance of properly designed, installed and maintained firestops can not be stressed enough in both of the cases.

Because in the case of fire there is always people in danger, and their decisions and actions can affect the outcome of the fire, it is essential that fire compartmentation functions as it is designed to function. Fire compartmentation consists of fire barriers and due to service installations and such, there are penetrations, which must be sealed effectively. If firestops in these cases are ignored fire barriers lose their integrity and ability to slow down the spreading of fire. Therefore firestops and materials used as well as their behavior in high temperatures should be well known and predictable.

The results achieved in experimental study were little surprising on some aspects and expected for some other. Long heating and cooling times of the oven restricted the maximum temperature which could be used in tests, and in the case of 800°C, test samples were severely damaged. Consequently firestop mastics had been deteriorated so much that only visual inspection was possible. If this heating process was set up differently, maybe so that temperature had just risen to 800°C and the cooling would have started immediately, the results may have been different. Other option would have been to settle for a lower temperature, for example 600°C, and use same heating and cooling times.

Most interesting results in visual inspection were achieved from testing at 200°C. It was surprising that already in relatively low temperature, in comparison with temperatures during compartment fire, some firestop mastics lost some of their properties. Furthermore this happened also to the mastic which is intended to be used especially in penetrations consisting of plastic pipes.

Heating tests at 800°C showed that FR220 gypsum mortar endures well at high temperatures and even for long times. Although not used in same way in tests as other mastics, gypsum mortar had only slight cracks and no sign of spalling. Usage of gypsum mortar, instead of concrete, as a filling of large penetrations can be adviced in case of non-load bearing structure.

Firestop mastics overall behaved in expected or easily predicted way during tests. Only at 200°C the result with FS701 and FS705 was something that was not predicted. But this is not comparable to the varying of behavior of the SP525. Non-fireproofed sealant mastic lacks the temperature resistance of other mastics used in tests and therefore deformations and adhesion lost was unpredictable and inconsistent among test samples.

Weight losses were in most cases expected and did not really provide much information. More informative approach would have been weighting concrete test samples without mastics and with mastics so only the weight loss of concrete could have been determined. Also this way the weight losses of sealant mastics would have been possible to estimate to some extend.

Regarding mechanical properties, only compression strengths of both types of concrete were tested. Compression tests after exposure to the lower temperature of 200°C were done in a more advanced maturity than 28 days. However, tests indicated that heating times and maximum temperature used for compression test samples did not effect negatively to the compression strength of neither concrete type.

The adhesion between concrete and firestop mastic is important during the whole life cycle of fire barrier. This is also true in the case of fire and in temperatures around 200°C. Exposure times to temperatures below 600°C in the case of fire can be long if the available oxygen is limited due to ventilation. Therefore tested scenario is possible in building fires and can potentially cause the premature failing of firestops if the fire is not detected during the growth phase.

SEM examination did not provide much information. There were no signs of suspected penetration of mastic inside the concrete. However, examination of gypsum based FR220 samples reinforced observation made in visual inspection about concretes worse condition comparing to other mastic samples. FR220, or any other gypsum designed for firestopping, could cause faster damaging of the concrete when exposed to high temperatures.

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List of Appendices

Appendix A Concrete mix design, OPC

1/8/2014

Test:	OPC (CG2 0,15% sp)		
	compromise grading		
Date:	10/31/2013	Person:	
Time:		Plant:	

40 Ltr.

%amount of equivalent binder		Mix proportions [kg/m³]	Batch size 8.0 liters / Measured amounts [kg]	Eur/t	Eur/m3	CO2/m3
0.00	0.00 BFS Finnsementi	0.0	0.000	70	0.0	0.0
0.00	0.00 FLY ASH (nantali 2011)	0.0	0.000	15	0.0	0.0
100.00	1.00 CEM I 52.5 wt% 1.000	300.0	2.400 12	90	27.0	240.0
	0.00 limestone Nordkalk	0.0	0.000	35	0.0	0.0
	0.00 FA not counted as binder	0.0	0.000	15	0.0	0.0
	0.00 BFS not counted as binder	0	0.000	70	0.0	0.0
	1.00 Total:	300	2.400 12			
Aggregate 1	filleri	473	3.782 18,92	10	4.7	1.9
Aggregate 2	0-0,6	73	0.582 2,92	10	0.7	0.3
Aggregate 3	0,5-1	0	0.000 0	10	0.0	0.0
Aggregate 4	1-2	145	1.164 5,8	10	1.5	0.6
Aggregate 5	2-5	182	1.455 7,28	10	1.8	0.7
Aggregate 6	5-10	236	1.891 9,44	10	2.4	0.9
Aggregate 7	8-16	709	5.674 28,36	10	7.1	2.8
Aggregate (dry total)		1818	14.548 72,72			
Total water amount		192				
Britesil H20	0%	0.000	0.000	450	0.0	0.0
Sodium hydroxide (NaOH)		0.0	0.000			
Sodium carbonate (Na2CO3)	0%	0.0	0.000	250	0.0	0.0
Potasium carbonate (KCO3)	0%	0.0	0.000	600	0.0	0.0
SP	0.15 %	0.5	0.004 0,02			
Extra added Water (excludingWG)		195.3	1.562 7,812	Total	45.2	247.3
W/Powder	0.640					
Modulus	#####					
NaOH, %	0.0					
Temp curing	20 °C					
Temp concrete	°C					

~~name?~~ VB-Parmix

Sample weigh	1950 g
Calculated target	2265 kg/m

~~What tests to wet concrete?~~

Appendix B Concrete mix design, HPC

K80, 28d							
valkosementti + 7% silika	0,07						
16mm maksimiraekoko							
ilmamäärä 1%	10	kg/m3					
silikan määrä	0,07	*C					
kuvaajista saadut arvot							
sementin ja sideaineen määrä, yhteensä							
K80, olet hajonta 10MPa, K90 ->	X	kg/m3					
sementin määrä, C	400	kg/m3					
notkistinta kuvaajasta	2,50 %						
Vesisementti-suhde	0,35						
1. Suhteituslujuus K.s							
oletetaan hajonnan olevan 10 Mpa							
->	90	Mpa					
2. Sideainemäärä							
C+2,5Si+0,3Lt+Mk =	S	kg/m3	C=400, Si=0,07*C				
C+2,5*0,07C =	S	kg/m3					
S=	470	kg/m3					
Si=	28	kg/m3					
3. Tehonotkistimen määrä							
0,02*(C+Si)=	10,7	kg/m3	Use only half of this				
	5,35		0,428	->	0,214	kg	
4. Vesimäärä							
(W+Nt+I)/S=	0,35						
(W+Nt+I)/(C+2.5*SI)=	0,35						
	0,35						
W= (w/c)*(C+2,5*SI)-NT-I	143,8	kg/m3	->	5,752	kg		
5. Runkoaineen määrä betonin perusyhtälöllä							
(Q.R/rho.R)+W+Nt+I+(Qc/rho.c)+(Q.Si/rho.Si)+(Q.Lt/rho.Lt)+(Q.Mk/rho.Mk)=1000							
->							
(Q.R/2.68)+144.4+6.6+10+(318.2/3.1)+(12.7/2.2)=1000							
Q.R=(1000-144.4-6.6-10-(318.2/3.1)+(12.7/2.2)*2.68							
C/3.1=	129,0323	kg/m3					
Si/2.2=	12,72727	kg/m3					
Q.R =	1859,224	kg/m3					

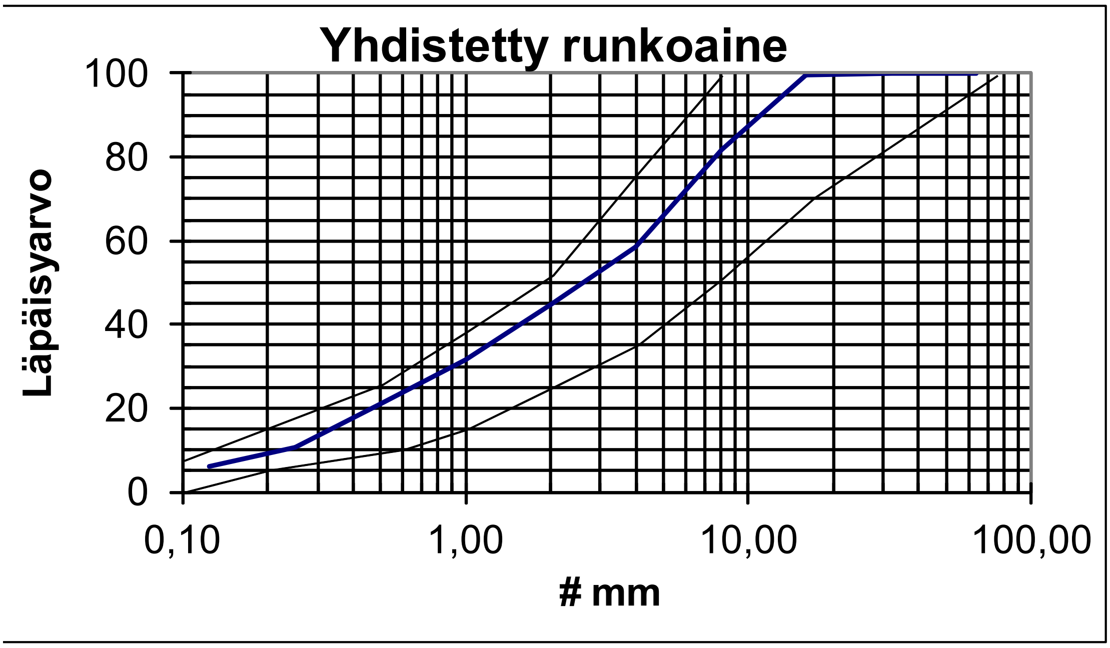
BETONIN KOOSTUMUS N:o

Rakentaja		Rakennustyö HIGH STRENGTH			
Rakenneosat					
Betonin luokka ja nimellislujuus	K80	Sementin merkki	valkoseme	Suurin raekoko # 16	Lisäaineen nimi VB-Parmix
		Tavoitenotkeus s VB	3	Sepeliä %	
Tavoitelujuus MN/m²		Vesi-ilma-sementtisuhde	0,35	Rakeisuusluku H	Annostus % sem. massasta 2,5
Suhteituslujuus MN/m²	90			Ilmamäärä dm³/m 10	

Runkoaineet Tunnus		Humus	Liete	Rakeisuus 0,125	0,25	0,5	1	2	4	8	16	32	64	H
a	Filleri			68,9	89,7	96,5	98,9	99,4	99,7	100	100	100	100	953
b	0.1-0.6			4	30	88	100	100	100	100	100	100	100	822
c	0.5-1.2			0	0	23	96	100	100	100	100	100	100	719
d	1-2			0	0	1	13	86	100	100	100	100	100	600
e	2-5			0	0	0	0	1	40	100	100	100	100	441
f	5-10			0	0	0	0	0	2	48	100	100	100	350
g	8-16			0	0	0	0	0	0	5	96	100	100	301
Runkoaineiden yhdistäminen	a	8	%	6	7	8	8	8	8	8	8	8	8	76
	b	12	%	0	4	11	12	12	12	12	12	12	12	99
	c	10	%	0	0	2	10	10	10	10	10	10	10	72
	d	17	%	0	0	0	2	15	17	17	17	17	17	102
	e	28	%	0	0	0	0	0	11	28	28	28	28	123
	f	13	%	0	0	0	0	0	0	6	13	13	13	46
	g	12	%	0	0	0	0	0	0	1	12	12	12	36
Yhdistetty runkoaine				6	11	21	32	45	58	82	100	100	100	554

100

Aine-osat	Suhteutusseos kg / m³ (dm³ / m³)	%	kg / m³	Kiintotiheys kg / m³	dm³ / m³	Runkoaineen vesipitoisuus %	kg	Työseos A kg / m³	Irtotiheys kg / dm³	Työseos B dm³ / m³	Annos m³ 0,04
Sementti	400		318,2	3,1		-------	-------				
Runko-aine		8 a	148,738	2,68		0,6	0,8924	147,845			5,91382
	-------	12 b	223,107	2,68		0,6	1,3386	221,768			8,87073
	1859,22	10 c	185,922	2,68		0,6	1,1155	184,807			7,39227
		17 d	316,068	2,68		0,6	1,8964	314,172			12,5669
		28 e	520,583	2,68		0,6	3,1235	517,459			20,6984
		13 f	241,699	2,68		0,6	1,4502	240,249			9,60996
	-------	12 g	223,107	2,68		0,6	1,3386	221,768			8,87073
Vesi	143,8	-------		1,00		-------	11,155	132,645			5,30579
Ilma	10	-------	-------	-------		-------	-------	-------	-------	-------	-------
Yhteensä	2413,02	-------		-------	1000	-------	-------	1980,71	-------		79,2285



Appendix C Schedule for manufacturing and testing

Date	Work phase
13.1.	Casting OPC
14.1.	Demolding OPC
15.1.	Casting HPC
16.1.	Demolding HPC
17.1.-9.2.	Curing OPC and HPC
10.2.	28d strength test OPC
	Cutting and drilling
12.2.	28d strength test HPC
	Cutting and drilling
12.2.-16.2.	Drying OPC and HPC
17.2.	Pipes and sealing of joints OPC
19.2.	Pipes and sealing of joints HPC
	Filling holes with FR220
20.2.-16.3.	Curing mastics
17.3.	Heating tests begin
	OPC to 200°C
18.3.	Visual inspection of OPC 200°C
	HPC to 200°C
19.3.	Visual inspection of HPC 200°C
	OPC to 800°C
20.3.	Visual inspection of OPC 800°C
	HPC to 800°C
21.3.	Visual inspection of HPC 800°C

Appendix D Compression strength test results, OPC

0 TESTCERTIF.
===========

test of compr. strength
acc. DIN 1048 part 1

plant ___ to test report no.: OPC

specimen identificat.

operat: ....
casting day: 1301................
test age: ....

strength class: ....
testday: 1002................

Vers. Nr.	Probenkennzeichen	specimen dimensions shape: PRISM l mm	b mm	h mm	mass kg	raw dens. kg/dm3	test face mm2	maximal load kN	compr. stren. N/mm2	remarks
1	1	100.2	100.2	100.3	2.344	2.328	10040.0	384.7	38.32	
2	2	99.7	99.7	100.5	2.319	2.321	9940.1	393.5	39.59	
3	3	100.2	100.2	100.7	2.338	2.312	10040.0	387.9	38.64	
mean values of 3 valid tests						2.320			38.85	

Appendix E Compression strength test results, HPC

0 TESTCERTIF.

===========

test of compr. strength
acc. DIN 1048 part 1

plant ___ to test report no.: HPC

specimen identificat.

operat: ....

casting day: 1501...............

test age: ....

strength class: ....

testday: 120214.............

Vers. Nr.	Probenkennzeichen	specimen dimensions shape: PRISM l (mm)	b (mm)	h (mm)	mass (kg)	raw dens. (kg/dm3)	test face (mm2)	maximal load (kN)	compr. stren. (N/mm2)	remarks
1		100.0	100.0	100.0	2.433	2.433	10000.0	961	96.1	
2	2	100.4	100.4	100.5	2.473	2.441	10080.2	1013	100.5	
3	3	100.4	100.4	100.1	2.452	2.430	10080.2	951	94.3	
mean values of 3 valid tests						2.435			97.0	

Appendix F Heating test runs, Temperature observations and notes

t (min)	T (C)	Notes
0	22	
10	84	
20	218	END OF WARMING (t1)
30	200	(t2)
40	200	
50	200	
60	200	
70	200	
80	200	OFF (t3)
90	186	
100	174	TOP HATCH OPEN
110	165	
120	160	DOOR OPEN
130	132	
140	115	
150	105	
160	95	
170	88	
180	85	
190	69	

t (min)	T (C)	Notes
0	22	
10	127	
20	214	
30	336	
40	405	
50	505	
60	579	(t1)
70	601	(t2)
80	600	
90	600	
100	600	
110	600	
120	600	OFF (t3)
130	558	
140	529	
150	506	TOP HATCH OPEN, DOOR OPEN
160	450	
170	407	
180	381	
190	357	
220	297	
240	265	
250	249	
260	237	
270	225	
290	175	
300	157	
310	147	
330	98	
340	85	

t (min)	T (C)	Notes
0	22	
10	84	
20	198	END OF WARMING (t1)
30	213	(t2)
40	200	
50	200	
60	200	
70	200	
80	200	OFF (t3), DOOR OPEN 1cm
90	167	
100	142	
110	123	
120	113	
130	105	
140	99	DOOR OPEN 5cm

t (min)	T (C)	Notes
0	22	
10	80	
20	184	
30	286	
40	399	
50	482	
60	576	
70	642	
80	710	(t1)
90	772	
96	800	(t2)
100	800	
110	800	
120	800	
130	800	
140	800	
150	800	
156	800	OFF (t3)
160	773	
170	728	
180	700	
190	676	HATCH OPEN, DOOR OPEN
200	604	
210	564	
220	536	DOOR OPEN 1CM
260	415	
320	324	
440	196	LAB CLOSED

Appendix G Compression strength test results after heating, OPC

0 TESTCERTIF.

test of compr. strength
acc. DIN 1048 part 1

plant ___ to test report no.: OPC

specimen identificat.

operat: ....
casting day: ....
test age: ....

strength class: ....
testday: 1504................

Vers. Nr.	Probenkennzeichen	specimen dimensions shape: PRISM l mm	b mm	h mm	mass kg	raw dens. kg/dm3	test face mm2	maximal load kN	compr. stren. N/mm2	remarks
1	1	101.1	101.1	99.8	2.282	2.237	10221.2	437.8	42.83	
2	2	100.2	100.2	100.3	2.273	2.257	10040.0	427.8	42.61	
3	3	100.4	100.4	100.1	2.267	2.247	10080.2	441.1	43.76	
mean values of 3 valid tests						2.247			43.07	

Appendix H Compression strength test results after heating, HPC

0 TESTCERTIF.

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test of compr. strength
acc. DIN 1048 part 1

plant ___ to test report no.: HPC

specimen identificat.

operat: ....
casting day: ....
test age: ....

strength class: 90..................
testday: 1504................

Vers. Nr.	Probenkennzeichen	specimen dimensions shape: PRISM l mm	b mm	h mm	mass kg	raw dens. kg/dm3	test face mm2	maximal load kN	compr. stren. N/mm2	remarks
1	1	99.2	99.2	100.5	2.376	2.402	9840.6	1063	108.0	
2	2	100.2	100.2	100.2	2.377	2.363	10040.0	1069	106.4	
3	3	100.7	100.7	101.3	2.380	2.317	10140.5	993	98.0	
mean values of 3 valid tests						2.361			104.1	